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BAHÇEŞEHIR UNIVERSITY

ALLOCATION OF STOCKS IN A MULTI-ECHELON SPARE PARTS DISTRIBUTION SYSTEM

M.S. Thesis

Nil GİRGİN

ISTANBUL, 2011

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INDUSTRIAL ENGINEERING

Title of the Master's Thesis	: Allocation of Stocks in a Multi-Echelon Spare Parts Distribution System
Name/Last Name of the Student	: Nil GİRGİN
Date of Thesis Defense	: 25.01.2011

The thesis has been approved by the Graduate School of Natural and Applied Sciences.

Asst. Prof. Dr. Tunç BOZBURA

Acting Director

This is to certify that we have read this thesis and that we find it fully adequate in scope, quality and content, as a thesis for the degree of Master of Science.

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ACKNOWLEDGEMENT

I would like to express my sincere gratitude to Assist. Prof. Barış Selçuk for his supervision and guidance. Many thanks for constituting rudiments of inventory management methods, encouragement and constructive criticism throughout the duration of the study.

Also I would like to thank my current director Mr. Çınar D. Kurra for his valuable supports and understanding during whole Industrial Engineering master's program.

I would like to express my heartiest thanks to my dear friend MSc. Levent H. Dal in helping through the whole study with his advanced technical and computer skills also with continuous encouragement. The preparation of this master thesis would not have been possible without his support and endless patience. I would like to thank him again coming into my life.

And my deepest gratitude to my parents, my dearest aunt and sister in supporting and trusting me from the very beginning.

25.01.2011 Nil Girgin

ABSTRACT

ALLOCATION OF STOCKS IN A MULTI-ECHELON
SPARE PARTS DISTRIBUTION SYSTEM

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Industrial Engineering Program

Supervisor: Assist. Prof. Barış Selçuk

January, 2011, 74 pages

This master thesis is motivated from real life spare parts inventory control systems in which different managerial control approaches are utilized. It is a common practice in multi-echelon inventory systems that the stocks are controlled as adaptation of single echelon models for various reasons such as; ease of organizational control, performance monitoring and also interdepartmental conflicts. Therefore, although centralized control has been proved to be efficient from a theoretical perspective, decentralized control is still preferable especially in multi-echelon systems. This study will provide a guideline on how to design a decentralized system as compared to the centralized system. In this study a two-echelon multi-item spare parts inventory control system is considered. Because of the nature of spare parts, inventory is controlled on an (s-1,s) basis with continuous review. For both centralized and decentralized models a greedy algorithm procedure is suggested in order to get results that originated from managerial differences out in the open.

Key Words: Multi-echelon system, Inventory control, Spare parts, METRIC

ÖZET

ÇOK BASAMAKLI YEDEK PARÇA DAĞITIM SİSTEMLERİNDE
STOK TAHSİSİ

Girgin, Nil

Endüstri Mühendisliği Programı

Tez Danışmanı: Yrd. Doç. Dr. Barış Selçuk

Ocak, 2011, 74 sayfa

Bu yüksek lisans tezi günümüzde farklı yönetimsel kontrol yaklaşımları uygulamakta olan yedek parça envanter kontrol sistemlerinden esinlenerek hazırlanmıştır. Günümüzde çok basamaklı envanter sistemleri yaygın olarak çeşitli sebeplerden ötürü tek basamaklı envanter modellerini uygulamaktadır. Tek basamaklı envanter modelleri kurumlara organizasyonel kontrolde ve performans denetimlerinde kolaylık sağlamaktadır. Bu modellerin tercih sebeplerinde yaşanılan departmanlar arası fikir uyuşmazlıkların rolü büyüktür. Teorik olarak merkezleştirilmiş yönetimin daha etkin olduğu kanıtlanmasına rağmen, merkezi olmayan yönetim biçimi özellikle çok basamaklı envanter sistemlerinde halen tercih edilmektedir. Bu çalışma merkezi bir sisteme göre merkezi olmayan bir sistemin nasıl tasarlanacağı konusunda genel bilgi sağlayacaktır. Çalışmada iki basamaklı ve çoklu ürün içeren yedek parça kontrol sistemi ele alınmıştır. Yedek parçaların doğası gereği sistemde sürekli gözlem ile (s-1,s) kontrol yönteminin kullanılması düşünülmüştür. Merkezi ve merkezi olmayan modeller için, yönetimsel farklılıklardan doğan sonuçları görebilmek adına algoritmalar önerilmiştir.

Anahtar Sözcükler: Çok basamaklı sistemler, Envanter kontrolü, Yedek parça, METRIC

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ABBREVIATIONS

Central Warehouse	:	CW
Due in	:	DI
External Supplier	:	EXS
Local Warehouse	:	LW
Multi Echelon Technique for Recoverable Item Control	:	METRIC

SYMBOLS

Average direct shipment time between CW and LW for all items	:	t^{EM1}
Average direct shipment time between EXS and LW for all items	:	t^{EM2}
Base-stock level of LW *j* for item *i* (or CW if $j = 0$)	:	s_{ij}
Daily demand rate of item *i* at CW	:	λ_{i0}
Daily demand rate of item *i* at LW *j*	:	λ_{ij}
Direct shipment cost from CW to LWs for all items	:	c^{EM1}
Direct shipment cost from EXP to LWs for all items	:	c^{EM2}
Expected backorder level of CW	:	EBO_0
Expected backorder level of LW *j*	:	EBO_j
Expected waiting time of CW		EWT_0
Expected waiting time of LW *j*	:	EWT_j
Fraction of demand for item *i* met by a direct shipment CW to LW	:	θ_{ij}
Fraction of demand for item *i* met by a direct shipment EXS to LW	:	γ_{ij}
Fraction of demand for item *i* met by the stock directly at CW	:	β_{i0}
Fraction of demand for item *i* met by the stock directly at LW	:	β_{ij}
Index for item number	:	i
Index for LW number	:	i
Inventory holding cost for item i at LW j	:	C_{ij}^h
Number of demands in pipeline random at a time	:	x
Pipeline of item *i* at CW	:	μ_{i0}
Pipeline of item *i* at LW *j*	:	μ_{ij}
Price of item *i*	:	c_i
Replenishment lead time of item *i* at CW	:	T_{i0}
Replenishment lead time of item *i* at LW *j*	:	T_{ij}
The set of all warehouses including CW	:	$N = \{0\} \cup N$
The set of items	:	I
The set of LWs	:	N
Total cost		TC
Total inventory investment (budget)	:	K
Transportation time between CW and LW	:	t_j
Variable {0,1}		α
Waiting time target of system	:	WT^{target}

1. INTRODUCTION

In various equipment intensive industries such as military services, railway and aircraft manufacturing, information and communication systems, spare parts inventory management has crucial importance for uninterrupted continuation of operations. Therefore, service providers try to achieve fast and reliable supply of spare parts. Some main goals of spare parts inventory management of a service provider are:

- Reducing inventory investment,
- Retaining current customers and gaining new customers,
- Maintaining operational availability of machines and equipments in order to reduce down-time of machines, which can be very costly,
- Providing competitive advantage to the company in market,
- Avoiding waste and redundant stock holding, which cause high inventory holding cost.

Because of these important aspects, there is a developed body of research for spare parts inventory management. When a manufacturer produces and sells a machine or product, after sales service must be provided to geographically dispersed customers in order to obtain reliability, customer loyalty and high service quality. These can be said as the key factors of successful business. In order to achieve high service levels for customers and sustain that level, response time to the costumer which is defined as the time takes to meet a requested item, has a critical role in inventory management. Since these customers are usually scattered over a large geographical area, many companies use an extensive distribution network of inventory locations in order to guarantee a short response time and a high service level.

In order to establish a common understanding in spare parts, a definition must be made. A spare part refers to the part requirements for keeping the equipment in healthy operating condition in case of a breakdown. Healthy and smooth operating condition of equipments can be sustained with preventive and predictive maintenance by meeting repair and replacement.

In Figure 1.1 a typical two-echelon spare parts resupply network is given. Demands for spare parts arise due to the failure of some equipment that is operated by customer. To repair that equipment, customer claims a spare part from the nearest LW (local warehouse) which is responsible for resupplying him. That LW where the part is ordered, supplies that part from its stock if it is available. If not, according to company's inventory structure claimed part can be obtained in different ways. For example, the part can be backlogged at LW and wait for normal replenishment from CW or emergency shipments can be done, such as; direct delivery from CW (central warehouse) and EXS (external supplier) or lateral transshipments from other LWs. As it is seen there are many ways to manage service parts resupply network. While making management decisions in inventory control, characteristics of products and resupply network are highly important issues as well as service targets and business politics of the company.

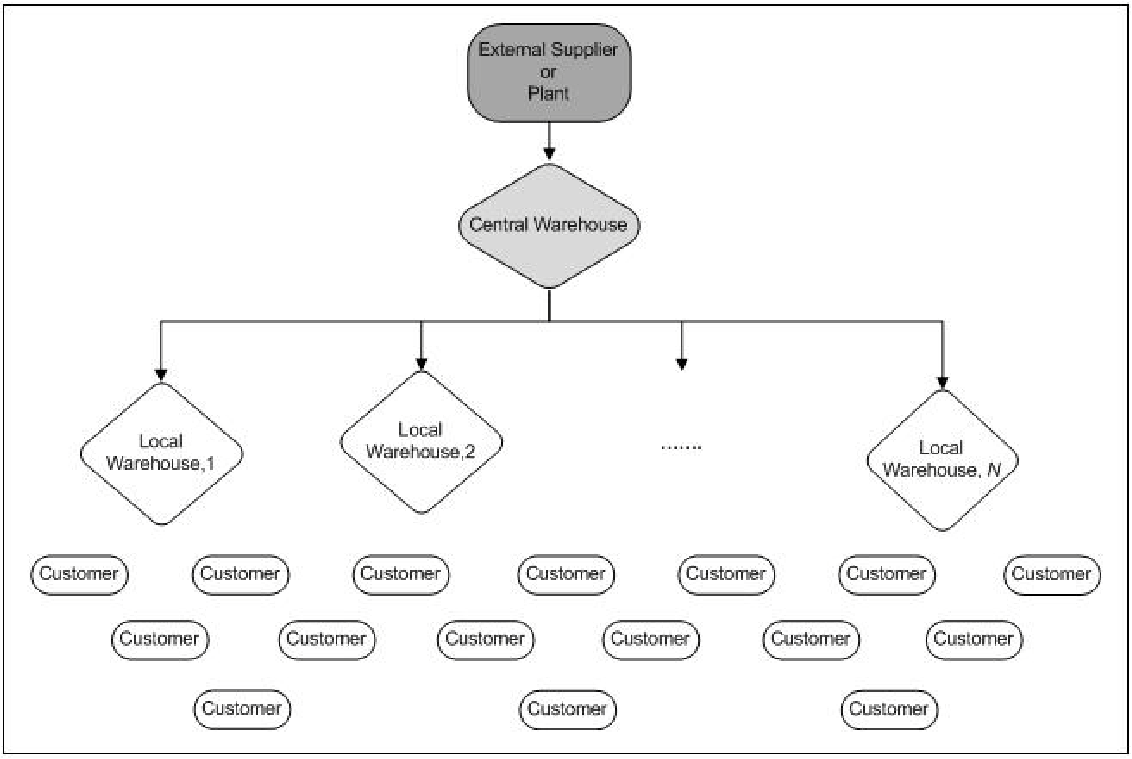

Figure 1.1 : Typical two-echelon service parts resupply network

In addition to resupply network and geographical importance of after sales spare part providers another major issue is allocating stocks of each item to each location, which directly effects customer response times. Decisions concerning what parts to stock at what locations are significantly important to the providers of the spare parts and customers. Therefore while making stock keeping decisions; nature of spare parts must be taken into considerations. As Sherbrooke (1968, p.122), Alfredsson and Verrijdt (1999, p.1416) and many others said spare parts typically have high cost and low demand rates.

Low usage and expensive items often present in inventory systems with a sizable fraction of total inventory investment up to 70 – 80 percent (Kukreja et al., 2001, p.1371). Given the nature of spare parts, the goal is to answer how much does a spare part provider or inventory manager need of each part to meet his company's service quality and profitability goals.

In this study, two-echelon inventory system is analyzed and optimal stock levels of spare parts are determined by employing two different mathematical approaches. Firstly; METRIC (Multi-Echelon Technique for Recoverable Item Control) model (Sherbrooke, 1968) in which total expected backorders of LWs are minimized subject to a budget constraint will be applied to a real life company data and to a random data set. The METRIC model is solved by the greedy algorithm, as also presented by Sherbrooke (1968), in a centralized way.

Greedy algorithm solution of METRIC will be focused on centralized and decentralized inventory management perspectives. In practice, the most frequent inventory management style is decentralized management style because of the simplicity of managerial authority, organizational control and performance monitoring. In addition to preference reasons of this managerial choice the conflicts of intercorporate relations can be said. These conflicts are originating from self-interest and ambition of managers most of the time. Both CW's and LWs' managers prefer to control their inventories as if they are independent departments. These choices lead to set individual service targets and business goals. As a consequence of separate decision making, excessive amount of inventory investments are used.

Greedy algorithm solution will compare both management styles and provide wide point of view about centralized and decentralized inventory management systems. In addition to METRIC model aforementioned two-echelon spare parts system will be examined by allowing emergency shipments in case of stock outs in LWs subject to a service level constraint. While determining optimal stock levels, model that is subject to evaluation is minimizing total inventory costs subject to average expected waiting time of customers as a service level constraint. Then again a greedy algorithm solution will be applied to the model in order to seek advantages and disadvantages of centralized and decentralized inventory management perspectives.

The main goal of the study is to implement basic inventory control models with different managerial perspectives and to represent strengths and weaknesses of these management choices.

Because of the characteristic of spare parts, in both mathematical models that are used in this study continuous review (s-1,s) replenishment policy (base stock policy) is adopted. This inventory control policy is very common in practice because of the high price and low demand nature of service parts. Same real life industry and random data sets will be used in both models.

In the remaining sections; firstly relevant research in literature will be reviewed briefly according to research topics, which is followed by model descriptions and results sections. Finally conclusions will be made.

2. LITERATURE REVIEW

The literature on multi-echelon inventory systems for service parts covers over 40 years of research. Sherbrooke’s (1968) Multi-Echelon Technique for Recoverable Item Control, shortly METRIC model, is generally accepted as the initiative model for service parts. METRIC model will be given in details in the subsequent sections because this study is mainly based on this model. Sherbrooke (1968) developed METRIC Model for US Air Force, which has a large class of repairable items. METRIC is a mathematical model of a base-depot system which determines optimal stock levels of warehouses that minimize expected backorders at the base level subject to a budget constraint. Model employs (s-1,s) inventory control policy with continuous review system in a two-echelon multi-item system where demand that occurs in bases is distributed by Poisson distribution. METRIC can also be operated as a single echelon inventory model. Sherbrooke’s (1968) METRIC model that motivated many inventory theories in literature will be explained in detail in the following Section 3.5.1.

Following METRIC; Muckstadt (1973) presents a mathematical model for the control of a multi-item, multi-echelon, multi-indenture system in repairable items, called MOD-METRIC. As Rustenburg et al. (2001, p.179) states Muckstadt (1973) is the first to recognize the importance of the product structure with respect to the recoverable item control. The objective of MOD-METRIC model is to describe the logistics relationships between an assembly and its subassemblies and to compute spare parts stock levels for both echelons and for assembly and subassemblies. MOD-METRIC is an extension of METRIC model that permits the explicit consideration of a hierarchical parts structure. While MOD-METRIC deals with modularly designed items, which have different modules with different criticality, METRIC assumes items with single-indenture and same essentiality. Although both models shares same general assumptions, they differentiate in indenture structures of items.

Another version of METRIC is improved by Slay (1980) and called VARI-METRIC model, which deals with multi-item, multi-echelon and single-indenture. Then an extension of VARI-METRIC is presented by Graves (1985). He analyzes a two-echelon spare parts inventory system with a continuous review (s-1,s) policy which consists of a repair depot and multi operating sites. Exact and approximation methods in setting steady-state inventory levels in the base and depots are presented in Slay's (1980) research. His model assumes that the failures are generated by a compound Poisson process same as Sherbrooke (1968), and shipment time from the repair depot to each operating sites is deterministic, unlike Sherbrooke (1968). Graves(1985) concludes that METRIC results in a wrong decision in 11.5 percent of the cases that he examined and in all of the cases METRIC approximation recommends less stock than it is actually required.

Sherbrooke (1986) uses Graves's (1985) approximation to improve Muckstadt's (1973) MOD-METRIC model. He suggests a two-indenture, two-echelon version of VARI-METRIC. Results that have been shown by his approach are fairly accurate than METRIC. He concludes that VARI-METRIC model that has been improved by Graves (1985) is more accurate than METRIC because while METRIC uses mean values only, VARI-METRIC uses variances as well. VARI-METRIC model, which both Graves (1985) and Sherbrooke (1986) have suggested, differentiates from METRIC model with multi-indenture approach, use of negative binomial distributions in steady state probabilities and utilizing variances together with mean values.

VARI-METRIC models are implemented in highly technology-driven environments by Rustenburg et al. (2001). They explore applicability of VARI-METRIC models in highly technology-driven environments such as Royal Netherlands Navy, RNLN. As Sherbrooke (1968) initiated spare parts management policies at US Air Force, they aimed to guarantee a sufficiently high availability of ships and technical systems in Royal Netherlands Navy while at the same time reducing inventory investment. They question applicability of VARI-METRIC (Slay, 1980; Graves, 1985; Sherbrooke, 1986) model and identify shortcomings of these VARI-METRIC models and also suggest solutions to overcome these shortcomings. They show that VARI-METRIC model has explicit advantages compared to the traditional item-approach which are currently in use at many organizations.

By using VARI-METRIC, low service levels of expensive products are compensating by high service levels of cheaper products which enables to achieve close-to-optimal availability. Also, they conclude that further research should include commonality, redundancy and condemnation issues which are critical in such environments.

As said before, METRIC model motivated many researchers into extensions of different supply alternatives in multi-echelon inventory systems. Muckstadt and Thomas (1980) was one of them who extended METRIC model with direct deliveries from the CW or EXS in case of stock outs at LWs. They assume whenever any LW is out of stock and a demand occurs, an emergency order is placed. They use two types of emergency orders which are direct shipments from CW and an EXS or plant; however, they do not allow lateral transshipments between LWs. Their objective is to allocate an inventory investment so as to minimize expected time to satisfy customer demand. They formulated two models; Item Decomposition (multi-echelon model) and Level Decomposition (single-echelon model) and compared them by minimizing inventory investment subject to demand-weighted fill rate constraints at the CW and at all LWs. These two models are solved by Lagrangian procedure with actual industrial data. They concluded that considerable savings can be obtained if an optimal multi-echelon model is used rather than a single-echelon one. Their model is much alike with one of the models in this study which is given in the section 3.5.2. With the same purpose, this study will focus on exploring centralized and decentralized managerial approach in multi-echelon inventory systems in addition to optimally setting stock levels. They named decentralized management approach as Level Decomposition where spare part providers act as an individual department as if in a single-echelon inventory system. Same approach will be used in this paper by applying both normal replenishment and direct delivery supplying options.

A single-echelon, single-item model, which analyzes optimal stock settings with normal replenishment orders, emergency repair orders and expediting of outstanding orders, is studied by Dhakar et al. (1994). They focus on high cost, low demand and critical repairable spare parts. Large share of inventory investments in many systems such as military and process industries consist of these items. Due to their nature, (s-1,s) inventory policy is suitable for these kinds of items. They present single-echelon, single-item mathematical model and an approach that can be used to find optimal stocking levels with three replenishment policies; normal replenishment orders, emergency repair orders and expediting of outstanding orders.

Also Cohen et al. (1986) considers a model of setting base stock levels in a single-item, multi-echelon distribution system subject to a single weighted average time-based fill rate constraint. The objective of the model is to minimize total holding and emergency shipment costs. Emergency shipments are made to satisfy demand shortages and their solution procedure solves one echelon at a time with the service level constraint evaluated once a lowest echelon solution is reached. In this thesis, while questioning different decision making perspectives of inventory managers, a similar model will be adopted as Cohen et al. (1986). This study will utilize different parameters and procedures such as; expected waiting time as a service performance measure, a different solution procedure, which calculates each echelon at the same time and multi-item approach unlike Cohen et al.(1986).

A different type of emergency shipment is discussed along with direct deliveries by many researchers, which are widely called lateral transshipment. Lateral transshipment refers to sharing on hand inventory with the locations in the same echelon, like between LWs. Some of the studies that utilize different performance measures and approaches are given in the following. Dada (1992) studies on two-echelon system with priority shipments and adopts two types of priority shipments; direct deliveries from CW and lateral transshipments. He also assumes if both priority shipments cannot satisfy demand, any item in transit from the CW to LW can be used to satisfy that demand.
Hausman and Erkip (1994) search the amount of suboptimization, which can occur if multi-echelon systems are managed as independent single-echelon systems. They considered low-demand high-cost items with a continuous review (s-1,s) inventory policy where all LW stock outs are met on an emergency ordering basis. In multi-echelon inventory management environment, there are two managerial approaches:

1. Independent single-echelon inventory management, in which LWs that are in the lowest echelon in the system are responsible for their own stocking policies

independent of each other and of the CW. The CW will determine its own single-echelon inventory policy which may be different form LW's performance objectives.

2. A multi-echelon inventory management in which inventory control decision is determined by taking interrelationship between the CW and the LWs into account where the system performance objective is optimized by the application of the multi-echelon control policy.

Hausman and Erkip explore effects of centralized and decentralized management procedures by using an improved version of single-echelon model of Muckstadt and Thomas (1980). They use same industrial data sample of Muckstadt and Thomas had used. They presents an improved single-echelon model which has approximate multi-echelon performance, and observed that as the total budget available to the system decreases, the quality of single-echelon solution relapses. The same purpose of Hausman and Erkip (1994) has been adopted by this thesis as mentioned before in Muckstadt and Thomas' (1980) model. In addition to direct deliveries like Hausman and Erkip, this thesis will examine normal replenishment situation in which none of the emergency resupply options are allowed.

Moinzadeh and Schmidt (1991) and Verrijdt et al. (1998) both use emergency resupply models with a threshold stock level. Moinzadeh and Schmidt (1991) investigate the use of emergency replenishments with a single-echelon model with deterministic lead times. In their model, when the stock levels, drop below a certain threshold value, and the remaining lead time for a pipeline order exceeds the lead time for an emergency order, an emergency replenishment is placed. In order to use information about pipeline, they assume constant replenishment times. Backordering and lost demand situation are both modeled by them. They present a technique for setting optimal stock level and threshold level that minimizes a cost function. Verrijdt et al. (1998) focus on emergency repair model in order to minimize down time of customer by placing an emergency repair order, which is fast and expensive. They suggest an emergency trigger level. When the number of serviceable repair parts is equal or below this emergency trigger level, demand will be satisfied by emergency repair action. They consider single-echelon model with (s-1,s) policy with Poisson process demand. As a performance measure fill rate and expected backorders are used. They compare their numerical results with Muckstadt and Thomas' (1980) results and they observe significant cost reductions when using their policy. Also their simulation results show that the distribution of the repair times has a negligible effect on the service levels.

In order to obtain high service levels at a low cost in inventory system for spare parts, a two-echelon inventory model with lateral transshipments and direct deliveries is considered by Alfredsson and Verrijdt (1999). Their model consists of a CW, which is resupplied by an EXS that has infinite supply and a number of LWs that are supplied by CW. As an inventory policy one-for-one replenishment and continuous review is chosen. They showed that the performance of the inventory system is insensitive to the lead-time distribution, and also they achieved considerable savings by using lateral transshipments compared to using only normal resupply.

Lee (1987) study a two-echelon model with one-for-one replenishment in which lateral transshipments are allowed. LWs are grouped into a number of pooling groups where each LW in the same group is assumed to be identical. When a demand occurs at a LW that has no stock on hand, a transshipment order is placed from one of the same group of LWs. If there is no stock available from the same group of LWs, demand is backordered. Lee (1987) compares solutions with simulations and suggests an algorithm for determining optimal stock in which costs are minimized subject to service level constraints.

Axsäter (1990) considered a single product, two-echelon one-for-one replenishment model in which lateral transshipments are allowed but not emergency shipments. In the model, demands are assumed to be Poisson distributed and when a demand cannot be satisfied by a LW's stock or via lateral shipments from other LW, it is backordered at the LW. He provides recursive procedure to determine the exact holding and shortage costs-, but his procedure does not provide any information on the steady-state distributions. Also he compares his results with Lee's (1987) model with the same assumption that all the LWs in the same pooling group are identical, he provides better results.

Pyke (1990) studies repairable items for electronic equipment on military craft with two-echelon system where lateral transshipments are allowed. He investigates especially the priority rules of allocating stocks in LWs and CW. He concludes that improvement of service performance by lateral transshipments is marginal when lateral transshipment times are decreasing, and also major gain is achieved on the limit when lateral transshipment times go to zero.

Sherbrooke (1992) presents a simulation study with two-echelon base-depot system for repairable items using lateral transshipments. Unlike Lee (1987) and Axsäter (1990) he allows delayed lateral transshipments. He assumes that an emergency lateral transshipment, is only issued it will arrive sooner than a pipeline unit. He that shows an average backorder reduction of 30 – 50 percent in only-depot–repairable items is possible.

Archibald et al. (1997) consider a multi-period, periodic-review model of a two-echelon inventory system in which transshipments can occur at any time during a period. The two-depot single-item inventory is formulated as a Markov decision process, and also, they extend their two-depot multi-item problem with limited storage place.

Kukreja et al. (2001) study a real life situation that a large electric utility with several power-generating plants located at different geographic locations. These plants are operated independently and maintain enough stock to satisfy their own demand. Plants have their own warehousing facilities. Plants usually interact only when there is an emergency requirement for an item and then that demand met by a lateral transshipment. However, there is no explicit consideration to this interaction while determining their inventory policies. In order to offer an insight to this kind of situation, Kukreja et al. (2001) consider single-echelon multi-location continuous review system that allows transshipments, and also, a heuristic procedure is developed to determine cost-effective stocking levels. They showed that setting stock levels explicitly taking into account of full-pooling (transshipments), total inventory system cost could be reduced by approximately 70 percent over the company's decentralized policy. In this thesis centralized and decentralized policies of companies will be examined. As can be seen from Kukreja et al. (2001), inventory investment savings can be done by adopting different emergency supply models.

Sherbrooke (2004) considers all items in the system when making inventory level decisions. He uses system approach in lateral transshipments in his book. Most of the books on inventory modeling use item approach to determine stock levels, ignoring the impact of unit cost, echelon location, and hardware indenture. Because of this approach large reductions in inventory costs are obtained.

Wong et al. (2006) described a multi-item continuous review model of single-echelon system for spare parts with lateral transshipments and waiting time constraints. Objective of their model is to minimize the total costs for inventory holding subject to a target level for the average waiting time per demanded item at each echelon. Their solution procedure is based on Lagrangian relaxation that obtains both upper and lower bounds on the optimal cost. If a LW faces a demand that is out of stock, lateral transshipment from the other LW is applied. If the other LW has no stock on hand, an emergency replenishment from the CW is carried out. In their research they aim to advance the existing literature on multi-item inventory systems with lateral transshipments.

Kranenburg and Houtum (2009) consider a multi-item, multi-location, single echelon system where lateral transshipments are allowed with base stock control and aggregate mean time waiting constraints. They suggest a special structure within that single-echelon, which represents a form of partial pooling with no pooling and full pooling. Inventory pooling is referred to lateral transshipments. In their research partial pooling is described as “part of the locations has the ability to act as a provider of a lateral transshipment”. In order to determine the provider, they categorized LWs into two groups; main locals and regular local, where only main locals are allowed to provide lateral transshipments. They show partial pooling performs well compared to the full pooling. Moreover, when only a few LWs are allowed to provide lateral transshipment, a substantial part of the full pooling benefits are obtained.

During this study large scale of literature review has been done. Subsequent articles are not directly related to the research subject and purpose. However in order to look in a broad perspective into spare part inventory management, they are also included in literature review. Brief information about different research areas in inventory management can be found in the following.

Moinzadeh and Lee (1986) consider a single-item stock setting model in multi-echelon system. They also derive a decision rule to select (s-1,s) policy versus an (r,Q) policy. (r,Q) policy refers to reorder point “r” and reorder quantity “Q” for the inventory system. When system is controlled under an (r,Q) policy, an order of fixed quantity Q is places as soon as on hand inventory level drops to a reorder point r. They develop a two-parameter approximation to the distribution of backorders when CW follows (r,Q) policy.

Cohen et al. (1990) analyzed a multi-item, multi-echelon spare part system with periodic review subject to service level constraints. They develop an optimizer in order to set inventory policies for IBM. In problem solution they used level decomposition method for each facility and assumed that infinite resource available in resupply facilities such as CW or EXS.

Svoronos and Zipkin (1991) consider a multi-echelon system with stochastic transportation times between locations. They emphasis that system performance is sensitive to the transit-time distributions between stockage locations. They approximate steady-state behavior of the system and show that transportation time variances significantly affect the system performance.

Cohen et al. (1997) presented a benchmark analysis of technologically complex high-value products that focuses on after-sales service logistics systems. Their study aims to focus on especially computer industry. The study group, which is gathered from 14 different companies, has added other industries that have particular expertise in provision on service logistics support. The main purpose of the study is to survey current industrial practices and trends in service logistics operations, specifically the control systems utilized by each company, inventory stocking policies, information systems, communication systems and transport modes. This study searches for the best practice performance measures and evaluates most commonly used specific data, such as; a cost, revenues, control policies, etc. and also illustrates the contribution of after-sales service support function to firm competitiveness in high-technology industries.

Hopp et al. (1999) study two-echelon spare parts inventory system subject to a service level constraint. In their study, LWs are controlled by continuous review system (s-1,s) policy and they face Poisson customer demand. LWs resupplied by a CW which is followed by (r,Q) inventory policy. Their study focus on minimize system-wide inventory holding cost with an effective and easily implementable heuristics while keeping the average total delay at each location below a threshold level. Their heuristic decomposed the problem level by level by using Lagrangian relaxation.

Huiskonen (2001) discuss four control characteristics of spare parts: criticality, specificity, demand pattern and value of parts in terms of their effects on logistics system elements. Huiskonen's approach includes two choices; supply chain aspects that are the boundary-spanning role of the logistics and practitioners' purposes that performed such inventory controlling models. Improvement of the supply manager's understanding of control requirements of different types of spare parts is set as a main goal of the research.

Minner et al. (2003) focus on manufacturing flexibility on inventory investments in a distribution network consisting of two-echelon. They consider single product and two-echelon model consisting of a CW and multiple LWs with periodic review (s-1,s) policy. Manufacturing flexibility is batten on by planners while they are trying to reduce throughput time of a particular production order by giving this order priority at bottleneck work stations. Rescheduling of orders may lead to delay of other orders unless some excess capacity is available in order to prevent delay. Amount of excess capacity can be determined by the frequency of rescheduling, which is one of the measures of the manufacturing flexibility. They consider two problem formulations to investigate the trade-off between costs of manufacturing flexibility and costs of holding inventory. They examine cost for speeding up an order of a certain age and flexibility budget. In formulations fill rates at the LWs are taken into account and analyzed by Markov Chain Model. Their analysis yield good approximations for service levels and cost.

Caglar et al. (2004) examine Hopp's (1999) study with minor differences in a multi-item two-echelon system subject to average response time at each demand location. They use response time as a service constraint to minimize the system-wide inventory cost and show more effective solution than Hopp (1999). As a service constraint, response time, which is the average time it takes a customer to receive a spare part after a failure is used and during the solution response times are tired to maintain below a given threshold. In order to minimize total system investment, they use a mathematical approach, which is based on Lagrangian decomposition. Their heuristics perform well in large-scale problems.

Caggiano et al. (2009) suggest an optimization procedure in a multi-item, multi-echelon system with time-based customer service levels. In their model service level requirements are represented by channel fill rates which are the probabilities of incoming demands for a specific item at a specific location can be fulfilled within a specific period of time. They emphasis the importance of channel fill rates in time-based customer service agreements. Their mathematical model provides near-optimal solutions to the large-scale problems within a short time.

3. MODELS

The major goal of this master thesis is to present how managerial decisions affect inventory control systems of spare parts and their investments. Various reasons can affect in preference of inventory management style as explained previously. In practice, most of the companies prefer to manage their inventories as individual departments, which lead to high holding costs and waste of majority of inventory investment. Therefore this study will focus on effects of centralized and decentralized managerial decision making processes.

Two different inventory control models are considered. These models adopt different time-weighted performance measures. As it is known providing customer service is the primary function of the inventories that must be taken into account while assigning performance measures to the models. Both models deal with LW stock out situations, where CW stock outs situations only taken into account according to their influence on LWs.

In Model-1; a two-echelon, multi-item inventory control model is considered with regular resupply that is based on Sherbrooke's METRIC model (1968), only reparability excluded. In Model-2, as same as the first model, a two-echelon, multi-item control model is considered. In addition to regular resupplies, this time direct emergency shipments are allowed. Both models include decentralized versions with greedy algorithms so as to compare with centralized versions. Detailed information about model parameters, assumptions and objective functions will be given in the subsequent sections.

3.1 SPARE PART DEMAND

The demands of spare parts mostly depend on the output of preventive and predictive maintenance activities, and it is typically calculated based on mean time failure rates. Sudden unexpected breakdowns that can be caused by wrong operation of machines or missing a routine maintenance activity lead to a demand with no foreseeable. In practice, some industries include thousands of types of spare parts. Among all these variety, some parts fail or are needed more frequent than the others, which might have not been broken since 2 or 3 years. Therefore, it is a difficult and complex problem to figure out where demands are very low and costs are relatively very high, even the economic order quantity (EOQ) of spare parts is close to one (Sherbrooke, 2004, p.47).

Demand distributions of spare parts are crucial to inventory controlling models. In order to understand the behavior of spare part demand or failure rate and to reflect this behavior to the controlling models, a lot of research has been done. Common acceptance is that spare part failure follows a Poisson process (Muckstadt, 1973; Alfredsson & Verrijdt, 1999; Kukreja et al., 2001; Rustenburg et al., 2001; Caglar et al., 2004; Wong et al., 2006; Caggiano et al., 2009).

3.2 CONTROL POLICIES

As a consequence of spare parts nature, (s-1,s) continuous review policy is appropriate for both models. (s-1,s) policy also named as one-for-one replenishment, indicates that the inventory position drops to *s*-1, an order must be replaced for *s* units. Therefore, reorder point of this control policy is *s*-1 units. When a (s-1,s) policy is followed, an order is placed immediately whenever a demand occurs for one or more units of an item. It is widely used control policy in literature (Sherbrooke, 1968; Muckstadt, 1973; Muckstadt & Thomas, 1980; Graves, 1985; Sherbrooke, 1986; Dhakar et al., 1994; Verrijdt et al., 1998; Alfredsson & Verrijdt, 1999).

3.3 COST

Since repair service is excluded in both models, regular resupply transportation cost and repair costs are ignored. In Model-1 in which the model minimizes expected backorders subject to inventory investment, item holding cost is used. Let C_{ij}^{h} denote the inventory holding cost for item i at LW j for $i \in I$, $j \in N$. Then inventory holding cost for item i at LW j is;

$$C_{ij}^{h} = c_i s_{ij} \qquad \forall\, i \in I,\, j \in N \tag{3.1}$$

C_{ij}^{h} : Inventory s holding cost for item i at LW j

c_i : Price of item i

s_{ij} : Base stock level of item i at LW j for $i \in I$, $j \in N$

3.4 ASSUMPTIONS

1. As aforementioned, (s-1,s) inventory control policy is appropriate for every item in both echelons.
2. Emergency transportation costs and times are equal for each item.
3. Transportation costs for regular replenishment are ignored.
4. Condemnation is ignored.
5. As demand distribution Poisson process is assumed in both models.
6. Time and cost of repair service both in CW and LW is excluded.
7. EXS is assumed to have ample supply capacity.
8. Ordering costs are assumed to be zero.
9. Lateral transshipments are not allowed in both models.
10. In both models CW backorders are not explicitly considered. These backorders are of interest only as they influence the LW's backorders.
11. All items are equally essential and critical for the management.

3.5 MODEL FORMULATIONS

3.5.1 Model-1

In Model-1 Sherbrooke's (1968) METRIC model is employed. METRIC is a mathematical model of CW-LWs resupply system that minimizes expected backorders at LWs subject to an inventory investment with a system approach. In multi-echelon inventory control systems instead of system approach, item approach is a common practice where decisions on the number of spare parts units are made without considering other items. However in system approach, all items are considered and included in decision making process which enables decision maker (supply manager) to choose in different cost-effective alternatives.

As aforementioned in Section 2, Sherbrooke (1968) developed METRIC model for US Air Force where the total spare part inventory investment that approximately 5 billion dollars. He suggests a practical and efficient method which calculates optimal stock levels and distributions, also presents cost-effectiveness tradeoff for a large group of items. (Sherbrooke, 1968, pp.122-24).

Sherbrooke (1968) developed METRIC theory in two steps that are given below. Also detailed solution procedure of Model-1 and calculations parameters of the model will be given in Section 4.1.

1. Optimal allocation of stock levels between several LWs and CW.
2. Combining all items in the system by using marginal analysis.

Model-1 is considered as a two-echelon, multi-item inventory control system with (s-1,s) and continuous review policy which performs only normal replenishments, where emergency shipments are not allowed. Parameters that are used in Model-1 are given in Table 3.1.

Table 3.1 : Parameters of Model-1

Input Parameters	
c_i	Price of item *i*
t_j	Time to travel between CW and LW *j*
T_{i0}	Mean replenishment lead time of item *i* at CW by EXS
λ_{i0}	Daily demand rate of item *i* at CW
λ_{ij}	Daily demand rate of item *i* at LW *j*
K	Total inventory investment
Variables	
$EBO_0(s_0)$	Expected backorder at CW
$EBO_j(s_0, s_j)$	Expected backorder at LW *j*
x	Number of demands in pipeline random at a time
T_{ij}	Mean replenishment lead time of item *i* at LW by CW
Output Parameters	
$EBO_j(s_0, s_j)$	Expected backorder at LW *j*
s_{ij}	Stock level of item *i* at LW *j* for $i \in I$, $j \in N$

Objective function of Model-1 can be given as;

$$\min \sum_{j \in N-0} EBO_j\left(s_0, s_j\right) \tag{3.2}$$

subject to

$$\sum_{i \in I} \sum_{j \in N} c_i s_{ij} \leq \mathrm{K} \qquad \forall\, i \in I,\, j \in N \tag{3.3}$$

$$s_{ij} \in \mathrm{Z}^+ \cup \{0\} \qquad \forall\, i \in I,\, j \in N$$

where

$$EBO_j\left(s_0, s_j\right) = \sum_{i \in I} \sum_{x = s_{ij}+1}^{\infty} \left(x - s_{ij}\right) \frac{e^{-\lambda_{ij} T_{ji}\left(s_{i0}\right)} \left(\lambda_{ij} T_{ij}\left(s_{i0}\right)\right)^x}{x!} \qquad \forall\, i \in I,\, j \in N \tag{3.4}$$

$$T_{ij}\left(s_{i0}\right) = t_j + \frac{EBO_0\left(s_{i0}\right)}{\lambda_{i0}} \qquad \forall\, i \in I,\, j \in N \tag{3.5}$$

As can be seen from objective function expected backorder level of LW is depended to expected backorder level of CW. Because expected delay that originate from CW effects replenishment lead time of LW, $T_{ij}\left(s_{i0}\right)$. For this reason in Model-1 firstly CW's expected backorder level that depends on CW's stock, $EBO_0(s_0)$, is calculated Then according to the expected delay of CW, expected backorder level of LW j, $EBO_j(s_0, s_j)$ is calculated for each LW in the inventory system. As can be seen in Table 3.1, Model-1 gives total expected backorder level of LW j and stock levels of each item in the system as outputs.

3.5.1.1 Demand fulfillment process of model-1

In Model-1 that a demand for a particular item is fulfilled by LW if there is stock on hand available in LW. If the demanded item is not available or if there is no available ready-for-use part in the LW's stock, it is backordered in that LW. LW waits for replenishment from CW. In a similar way, CW replaces LW's orders either directly from its stock or demand is backordered in CW. CW will order replenishment from an EXS. As it can be seen where in both echelons backordering is allowed while emergency shipments are not. Resupply network of Model-1 can be seen in the following.

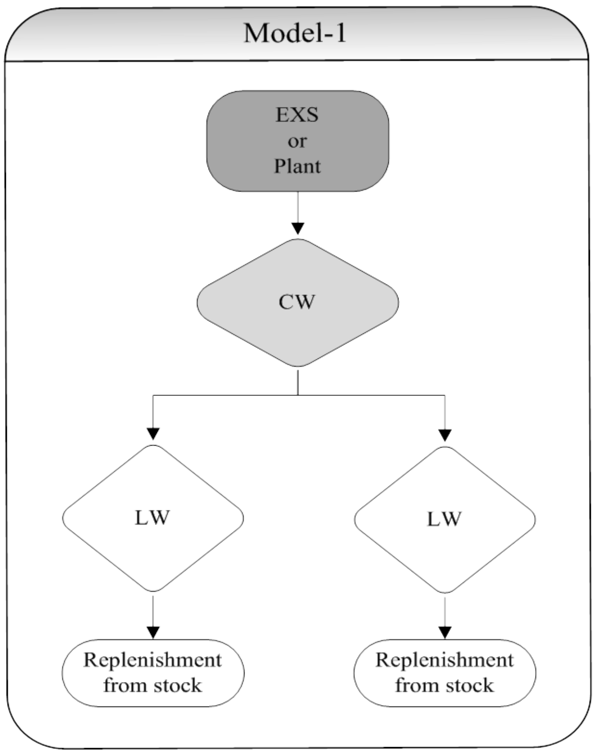

Figure 3.1 : Resupply network of Model-1

3.5.2 Model-2

Model-2 deals with a two-echelon, multi item inventory control system with (s-1,s) continuous review policy. As well as the regular replenishments, this model also performs two types of emergency shipments which are direct shipment from CW or EXS. Model-2 is considered as a mathematical model which minimizes inventory investment subject to a waiting time constraint. Waiting time refers to the time that is needed to satisfy customer demand. Model is allocating stocks optimally according to the given waiting time target.

Similar model is used by Muckstadt and Thomas (1980) and Hausman and Erkip (1994) as explained in details in Section 2. Their model assumes that whenever a demand occurs at LW and LW has no stock ready-to-use, an emergency order is placed. They calculated service levels and total costs by using an approximate method.

Objective function of Model-2 can be given as;

$$\min \sum_{i \in I} \left(\sum_{j \in N} c_i s_{ij} + \sum_{j \in N-0} c_{ij}^{EM} \right) \tag{3.6}$$

subject to

$$\sum_{i \in I} \left(\frac{\lambda_{ij}}{\sum_{i \in I} \lambda_{ij}} EWT_{ij} \right) \leq WT_j^{\text{target}} \qquad \forall\, j \in N-0 \tag{3.7}$$

$$s_{ij} \in \mathrm{Z}^{+} \cup \{0\} \qquad \forall\, i \in I,\, j \in N$$

where

$$EWT_{ij} = \beta_{ij}.0 + \theta_{ij}.t_j^{EM1} + \gamma_{ij}.t_j^{EM2} \qquad \forall\, i \in I,\, j \in N \tag{3.8}$$

$$c_{ij}^{EM} = \lambda_{ij}.\theta_{ij}.c_{ij}^{EM1} + \lambda_{ij}.\gamma_{ij}.c_{ij}^{EM2} \qquad \forall\, i \in I,\, j \in N \tag{3.9}$$

Input-output parameters and variables of Model-2 that are displayed in objective function above can be seen in Table 3.2 with definitions.

Table 3.2 : Input and output parameters of Model-2

Input Parameters	
c_i	Price of item *i*
t_j	Time to travel between CW and LWs
T_{i0}	Mean replenishment lead time of item i at CW by EXS
λ_{i0}	Daily demand rate of item *i* at CW
λ_{ij}	Daily demand rate of item *i* at LW *j*
c_{ij}^{EM1}	Average direct shipment cost of LW by CW for all item *i*
c_{ij}^{EM2}	Average direct shipment cost of LW by EXS for all item *i*
WT_j^{target}	Target waiting time of LW *j*
t_j^{EM1}	Average direct shipment time between CW and LW *j* for all item *i*
t_j^{EM2}	Average direct shipment time between EXS and LW *j* for all item *i*
Variables	
EWT_{ij}	Expected waiting time of item *i* at LW *j* for $i \in I$, $j \in N$
c_{ij}^{EM}	Total emergency direct shipment cost of item *i* at LW *j*
β_{i0}	Probability of CW fulfills demand of item *i*
β_{ij}	Probability of LW fulfills demand of item *i*
θ_{ij}	Probability of direct shipment from CW to LW *j*
γ_{ij}	Probability of direct shipment from EXS to LW *j*
Output Parameters	
EWT_{ij}	Expected waiting time of item *i* at LW *j* for $i \in I$, $j \in N$
s_{ij}	Stock level of item *i* at LW *j* for $i \in I$, $j \in N$

In similar way with Model-1; expected delay of CW effects expected waiting time of LW *j*. Because in replenishment lead time calculation of LW expected delay that is originated from CW is included.

Model allocates each item that minimizes total system cost and achieves waiting time target. By applying marginal analysis it decides which item to stock and according to its marginal value item is selected. Then Model-2 compares system's total waiting time with target waiting time after adding this selected item into stock.

Since in case of stock out, backordering at LW is not allowed, emergency orders will be placed. For this reason, model employs two different emergency direct shipments, CW to LW and EXS to LW. These direct shipments have different costs which are c_j^{EM1} and c_j^{EM2}, respectively. Since in this study fixed ordering costs are ignored, emergency direct shipment costs include transportation charges. Also Model-2 assumes that emergency resupply times are equal for every item, which are t_j^{EM1} and t_j^{EM2}, such that $t_j^{EM1} \langle t_j^{EM2}$.

Expected waiting time is calculated from occurrence probabilities of emergency direct shipments and average direct shipment times between locations. When LW has the demanded item *i* in its own stock, customer demand is satisfied immediately which means expected waiting time of that item is zero. Probability of an emergency order is multiplied by average direct shipment time.

3.5.2.1 Demand fulfillment process of Model-2

In Model-2 an incoming demand is fulfilled by LW, if the item that is requested is available in stock. If the requested item is not in the stock, then CW makes a direct shipment to the LW, if it has the demanded part in its stock. If CW has not got ready-to-use item in stock, then EXS makes a direct shipment to LW. Because of this fulfillment procedure, backordering in not allowed in LWs, but exist in CW.

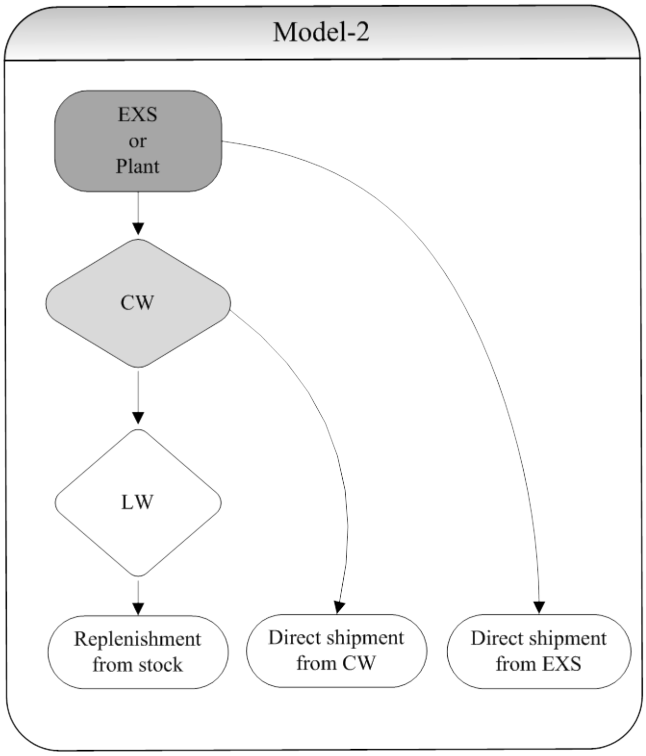

Figure 3.2 : Resupply network of Model-2

4. SOLUTION PROCEDURES

Two types of solution procedures which give approximate results are employed in this section. Firstly, before mentioned models' solutions will be explained. Then greedy procedures for each model will be applied in order to show how centralized and decentralized inventory management approach effects inventory control. Assumptions are given in Section 3.4 that are assumed in order to obtain computational advantage.

4.1 SOLUTION PROCEDURE FOR MODEL-1

As described in 3.5.1 section in Model-1, METRIC model (Sherbrooke, 1968) is utilized. METRIC model begins with calculating expected backorders at CW which is going to affect LW's backorders by causing a delay.

First average demand at the CW is calculated from Equation 4.1. As can be seen average demand of CW is the sum of demands of each LW. Then the average lead time demand is calculated. The term pipeline will be used though to study to denote the number of units of an item being resupplied to a warehouse from a higher echelon. Pipeline can be measured at any point in time by counting the number of units in resupply. CW' pipeline is calculated from Equation 4.2.

$$\lambda_{i0} = \sum_{j=1}^{N} \lambda_{ij} \tag{4.1}$$

$$\mu_{i0} = \lambda_{i0} T_{i0} \tag{4.2}$$

In order to compute expected delay at the LW, firstly expected backorder of CW is calculated. As it is assumed that failure rates (demand) are given by a Poisson process, the expected number of LW resupply request, which are outstanding at CW at a random point in time (Sherbrooke, 2004, p.49), is calculated as in Equation 4.3.

$$EBO_0\left(s_{i0}\right)=\sum_{i\in I}\sum_{x=s_{i0}+1}^{\infty}\left(x-s_{i0}\right)e^{-\lambda_{i0}T_{i0}}\frac{\left(\lambda_{i0}T_{i0}\right)^x}{x!} \tag{4.3}$$

In order to calculate expected backorder of LW, replenishment lead time that is effected by the delay of CW is calculated with Equation 4.4. Expected delay of CW is calculated according to Little's Law. Then pipeline of each item of LW is calculated according to Equation 4.5.

$$T_{ij}(s_{i0})=t_j+\frac{EBO_0\left(s_{i0}\right)}{\lambda_{i0}} \tag{4.4}$$

$$\mu_{ij}=\lambda_{ij}T_{ij}(s_{i0}) \tag{4.5}$$

Then expected backorder of LW is computed as in Equation 4.6.

$$EBO_j\left(s_{i0},s_{ij}\right)=\sum_{i\in I}\sum_{x=s_{ij}+1}^{\infty}\left(x-s_{ij}\right)e^{-\lambda_{ij}T_{ij}\left(s_{i0}\right)}\frac{\left(\lambda_{ij}T_{ij}\left(s_{i0}\right)\right)^x}{x!} \tag{4.6}$$

After computing expected backorder level of each LW, the model performs marginal analysis in order to set optimal stock levels subject to the given budget, given as inventory investment. In marginal analysis step, METRIC model decides which item to keep in which location. The decision of whether to hold stocks of item *i* at CW or not, directly affects the system performance. Because while computing LW lead time and LW expected backorder, CW's expected delay is used. Not having stock at CW will cause higher delay at LW, and as a result, lead time of LW will increase so as expected backorder at LW. Expected backorder of LW will be affected naturally by the decision to keep or not stocks at LW. For some items with very low failure rates, that has not been broken or failed since last three or four years, LW prefers not to hold stock of that slow moving item because of high holding cost. In this kind of situation CW step in to support LW. As a consequence of these effects marginal analysis is crucial to share stocks among LW and CW, which METRIC model performs efficiently. This stock sharing will be examined during the study in centralized and decentralized management approaches.

A marginal analysis example can be seen in Table 4.1. In this example, Model-1 is applied to CW-LW scenario for 10 items in order to demonstrate how it works. For ten items and a given budget (10000 €) the analysis performed 16 iteration and finished the given budget by sharing among CW and LW. In each iteration of the algorithm in order to determine next item that should be bought, only one number of each item is considered. The marginal value that is given in the last column of Table 4.1 provides all the information necessary for each item, which includes expected backorder reduction and item cost. In highlighted cells, each selected item that minimizes expected backorder in each iteration is given. In the final step algorithm finishes allocating inventory investment among CW and LW. There is an unspent amount left in the budget because all item prices are higher than 17 Euros.

Table 4.1 : Marginal analysis example with CW-LW scenario for 10 items and 10000 € given inventory investment

Item, location combination	S_{10}	S_{20}	S_{30}	S_{40}	S_{50}	S_{60}	S_{70}	S_{80}	S_{90}	S_{100}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	S_{18}	S_{19}	S_{110}	Cost, €	Total Expected Backorder	Marginal Value
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	42,61626372	
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	179,3000031	41,84318135	0,00431167
2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	358,6000061	40,615106	0,004115398
3	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	1	0	537,9000244	40,06546937	0,002157996
4	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	1	1	571,6000366	39,99761297	0,002013543
5	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	1	1	605,3000488	39,93377326	0,001824004
6	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	1	1	1	1710,300049	38,93454288	0,000904281
7	0	0	0	0	0	0	0	1	2	1	0	0	0	0	0	0	0	1	1	1	2815,300049	36,93891549	0,000903586
8	0	0	0	0	0	0	0	2	2	1	0	0	0	0	0	0	0	1	1	1	3920,300049	34,96535328	0,000894595
9	0	0	0	0	0	0	0	2	2	1	0	0	0	0	0	0	0	2	1	1	5025,299805	33,99981504	0,00087379
10	0	0	0	0	0	0	0	3	2	1	0	0	0	0	0	0	0	2	1	1	6130,299805	32,13741458	0,000865462
11	0	0	0	0	0	0	0	3	3	1	0	0	0	0	0	0	0	2	1	1	6309,599609	31,94818103	0,000847516
12	0	0	0	0	0	0	0	4	3	1	0	0	0	0	0	0	0	2	1	1	7414,599609	30,27239055	0,000802531
13	0	0	0	0	0	0	0	5	3	1	0	0	0	0	0	0	0	2	1	1	8519,599609	28,88480266	0,000700574
14	0	0	0	0	0	0	0	6	3	1	0	0	0	0	0	0	0	2	1	1	9624,599609	27,84358171	0,000568429
15	0	0	0	0	0	0	0	6	4	1	0	0	0	0	0	0	0	2	1	1	9803,899414	27,78863921	0,000262604
16	0	0	0	0	0	0	0	6	5	1	0	0	0	0	0	0	0	2	1	1	9983,199219	27,77495925	6,68055E-05

4.1.1 Model-1 Centralized

Model-1 centralized version follows the solution procedure that has given in the preceding section. As explained before, Model-1 firstly calculates the expected backorder level of CW, in order to obtain expected delay of CW on LW which is calculated according to the Little's Law. Then, by inserting CW's expected delay to LW's lead time and pipeline, the expected backorder of LW's are computed. After these computations the program starts to allocate stocks item by item according to a budget constraint. Thus, the model performs a marginal analysis, where it is seek for the item which reduces expected backorders more than other items. Marginal analysis algorithm examines each item to stock in which location. As mentioned in the previous section, it examines each item's effect on expected backorder of LW by computing marginal value. Marginal value is calculated by dividing expected back order reduction of each item-location combination to item cost. This shows the increase in system effectiveness per investment obtained when an additional unit of that item is selected to stock. The combination that has highest marginal value is chosen and the stock level of that combination is increased by one. The model keeps allocating stocks till the entire budget is spent. When algorithm selects an item, it compares current total amount of budget with given budget. If current amount exceeds the given budget constraint, than algorithm exclude that item, continue on the next one.

In order to sum up solution procedure of Model-1 centralized, pseudo code is given below. By analyzing item-location combinations, model suggests a centralized solution.

Initialize $s_{ij} \leftarrow 0 \qquad \forall \; i \in I$ **and** $j \in N$

$TC \leftarrow \sum_{i \in I} \sum_{j \in N} c_i s_{ij}$

$EBO_j\left(s_{i0}, s_{ij}\right) \leftarrow \sum_{i \in I} \sum_{x=s_{ij}+1}^{\infty} \left(x - s_{ij}\right) e^{-\lambda_{ij} T_{ij}\left(s_{i0}\right)} \frac{\left(\lambda_{ij} T_{ij}\left(s_{i0}\right)\right)^x}{x!}$

While $TC \leq K$

For each $i \in I$ **and** $j \in N$

$s_{ij} \leftarrow s_{ij} + 1$

$TC' \leftarrow \sum_{i \in I} \sum_{j \in N} c_i s_{ij}$

$EBO'_j\left(s_{i0}, s_{ij}\right) \leftarrow \sum_{i \in I} \sum_{x=s_{ij}+1}^{\infty} \left(x - s_{ij}\right) e^{-\lambda_{ij} T_{ij}\left(s_{i0}\right)} \frac{\left(\lambda_{ij} T_{ij}\left(s_{i0}\right)\right)^x}{x!}$

$\Delta EBO_j \leftarrow EBO_j - EBO'_j$

$\Delta TC \leftarrow TC' - TC$

$r_{ij} \leftarrow \frac{\Delta EBO_j}{\Delta TC}$

$\left(i^*, j^*\right) \leftarrow \arg\max_{i,j} \left\{r_{i,j}\right\}$

$s_{i^*, j^*} = s_{i^*, j^*} + 1$

End while

OUTPUT : s_{ij} **and** EBO_j

4.1.2 Model-1 Decentralized.

In Model-1 decentralized version, both CW and LW perform same stock allocation procedure as Model-1 centralized version but separately this time. In this model, CW and LW are thought as separate departments, which have different budgets and service performance targets. Basic idea of this greedy algorithm is, firstly, to allocate a given total inventory investment, say as budget, separately to the locations (to CW and to N number of LWs). Then each of the location sets stocks as if they are independent departments. Both of them perform marginal analysis that is explained in previous sections in order to determine optimal stock levels. In results section, different budget shares will be given to CW and LW, and then results will be compared with Model-1 centralized version. Pseudo code of greedy algorithm is given in the following.

Initialize s_{i0}, s_{ij} **and** $\alpha \leftarrow 0 \qquad \forall\ i \in I$ **and** $j \in N,\ \alpha \leftarrow \{0,1\}$

$TC_0 \leftarrow \sum_{i \in I} \sum_{j \in N} \mathrm{c}_i s_{i0}$

$EBO_0(s_{i0}) \leftarrow \sum_{i \in I} \sum_{x = s_{i0}+1}^{\infty} (x - s_{i0}) e^{-\lambda_{i0} T_{i0}} \frac{(\lambda_{i0} T_{i0})^x}{x!}$

While $TC_0 \le \alpha K$

For each $i \in I$

$s_{i0} \leftarrow s_{i0} + 1$

$TC_0' \leftarrow \sum_{i \in I} \mathrm{c}_i s_{i0}$

$EBO_0'(s_{i0}) \leftarrow \sum_{i \in I} \sum_{x = s_{i0}+1}^{\infty} (x - s_{i0}) e^{-\lambda_{i0} T_{i0}} \frac{(\lambda_{i0} T_{i0})^x}{x!}$

$\Delta EBO_0 \leftarrow EBO_0 - EBO_0'$

$\Delta TC_0 \leftarrow TC_0' - TC_0$

$r_{i0} \leftarrow \frac{\Delta EBO_0}{\Delta TC_0}$

$(i^*, 0^*) \leftarrow \arg\max_{i,0} \{r_{i,0}\}$

$s_{i^*,0^*} \leftarrow s_{i^*,0^*} + 1$

End while

OUTPUT: s_{i0} **and** EBO_0

$\forall\ i \in I$ **and** $j \in N$

While $TC_j \le (1-\alpha)K$

For each $i \in I$ **and** $j \in N$

$s_{ij} \leftarrow s_{ij} + 1$

$TC_j' \leftarrow \sum_{i \in I} \sum_{j \in N} \mathrm{c}_i s_{ij}$

$EBO_{0j}'(s_{i0}, s_{ij}) \leftarrow \sum_{i \in I} \sum_{x = s_{ij}+1}^{\infty} (x - s_{ij}) e^{-\lambda_{ij} T_{ij}(s_{i0})} \frac{(\lambda_{ij} T_{ij}(s_{i0}))^x}{x!}$

$\Delta EBO_j \leftarrow EBO_j - EBO_j'$

$\Delta TC_j \leftarrow TC_j' - TC_j$

$r_{ij} \leftarrow \frac{\Delta EBO_j}{\Delta TC_j}$

$(i^*, j^*) \leftarrow \arg\max_{i,j} \{r_{i,j}\}$

$s_{i^*,j^*} \leftarrow s_{i^*,j^*} + 1$

End while

$\alpha \leftarrow \alpha + 0{,}05$

OUTPUT: s_{ij} **and** EBO_j

4.2 SOLUTION PROCEDURE FOR MODEL-2

Outline of Model-2 is explained in Section 3.5.2. In order to reflect CW effects to the LWs, this model firstly considers CW calculations. In initial step, the model calculates expected delay that is originated from CW with the same procedure used in Model-1. However same equations are given again, in order to follow easily. Average total demand and pipeline equations are given in Equation 4.7 and 4.8, respectively.

$$\lambda_{i0} = \sum_{j=1}^{N} \lambda_{ij} \tag{4.7}$$

$$\mu_{i0} = \lambda_{i0} T_{i0} \tag{4.8}$$

$$EBO_0\left(s_{i0}\right) = \sum_{i \in I} \sum_{x=s_{i0}+1}^{\infty} \left(x - s_{i0}\right) e^{-\lambda_{i0} T_{i0}} \frac{\left(\lambda_{i0} T_{i0}\right)^x}{x!} \tag{4.9}$$

In order to obtain average delay on LW that is originated from CW, expected backorder of CW is calculated according to Equation 4.9. Then, the average CW delay is calculated form Little’s Law with Equation 4.10;

$$EWT_{i0} = \frac{EBO_0\left(s_{i0}\right)}{\lambda_{i0}} \tag{4.10}$$

Steady state probability for CW can be calculated as follows, where *x* is an integer and representing the number of parts in replenishment (resupply). β_{i0} denotes the probability of CW can meet a demand from its own stock.

$$\beta_{i0} = \sum_{i \in I} \sum_{x=0}^{s_{i0}-1} e^{-\lambda_{i0} T_{i0}} \frac{\left(\lambda_{i0} T_{i0}\right)^x}{x!} \tag{4.11}$$

After computation of CW expected delay, LW calculations will be done. CW's expected delay has a direct effect on LW's lead time so as LW pipeline. These variables are depended to average CW's delay as can be seen from Equation 4.10.

As explained in section 3.5.2.1, backordering at LWs are not allowed because in any stock out situation an emergency shipment is preformed. With the expected delay of CW, lead time of LW for each item *i* can be calculated as follows;

$$T_{ij}\left(s_{i0}\right) = t_j + EWT_{i0} \tag{4.12}$$

The pipeline of LW consists of due ins (DI) from resupply, in other words the number of items in resupply is calculated from;

$$\mu_{ij} = \lambda_{ij} T_{ij}\left(s_{i0}\right) \tag{4.13}$$

The probability of LW meeting a demand from its own stock can be calculated by using Erlang Loss Probability. Then;

$$L\left(c, p\right) = \frac{p^c / c!}{\sum_{x=0}^{c} p^x / x!} \tag{4.14}$$

In Equation 4.14; $L\left(c, p\right)$ denotes probability where c denotes stock levels in LW, s_{ij}, and p denotes pipeline of the LW, μ_{ij}. As for that the probability of LW can meet a demand from its own stock is;

$$\beta_{ij} = 1 - L(c, p) \tag{4.15}$$

In final step; emergency shipment probabilities are calculated. For $i \in I$, $j \in N$ let θ_{ij} denotes the fraction of demand for item *i* met by direct shipment from CW to LW j and γ_{ij} denotes the fraction of demand for item *i* met by direct shipment from EXS to LW j. Then;

$$\theta_{ij} = \beta_{i0}\left(1-\beta_{ij}\right) \tag{4.16}$$

$$\gamma_{ij} = \left(1-\beta_{i0}\right)\left(1-\beta_{ij}\right) \tag{4.17}$$

4.2.1 Model-2 Centralized

Model-2 centralized version follows the solution procedure that is given in preceding section. The model firstly calculates the expected backorder of CW, in order to compute expected delay on LW that is caused by CW according to the Little's Law. Then by inserting CW's delay to LW's lead time and pipeline, probability that LW can meet a demand from its own stock is calculated by Erlang Loss Probability equation. According to CW and LW steady state probabilities calculations, emergency direct shipments probabilities are calculated.

As mentioned section Model-23.5.2, model firstly allocates stocks that minimize total inventory cost. In each step of cost analysis, model selects the item that gives maximum reduction in total cost. Then in some point where total cost no longer minimized, model performs a marginal analysis, where it is seek for the item which reduces expected waiting time more than other items. The item which gives the lower marginal value is chosen. Pseudo code of Model-2 centralized is given below.

Initialize $s_{ij} \leftarrow 0 \qquad \forall\, i \in I$ **and** $j \in N$

$$TC \leftarrow \sum_{i \in I} \left(\sum_{j \in N} c_i s_{ij} + \sum_{j \in N-0} c_j^{EM} \right)$$

While $\Delta TC \langle 0$

For each $i \in I$ **and** $j \in N-0$

$s_{ij} \leftarrow s_{ij} + 1$

$$TC' \leftarrow \sum_{i \in I} \left(\sum_{j \in N} c_i s_{ij} + \sum_{j \in N-0} c_j^{EM} \right)$$

$\Delta TC \leftarrow TC - TC'$

$r_{ij} \leftarrow \Delta TC$

$\left(i^*, j^*\right) \leftarrow \arg\min_{i,j} \left\{ r_{i,j} \right\}$

$s_{i^*,j^*} \leftarrow s_{i^*,j^*} + 1$

End while

Initialize $WT_j^{\textbf{target}}$

$$EWT_{ij} \leftarrow \frac{\lambda_{ij}}{\sum_{i \in I} \lambda_{ij}} EWT_{ij}$$

While $EWT_{ij} \leq WT_j^{\textbf{target}}$

For each $i \in I$ **and** $j \in N-0$

$s_{ij} \leftarrow s_{ij} + 1$

$$EWT_{ij}' \leftarrow \frac{\lambda_{ij}}{\sum_{i \in I} \lambda_{ij}} EWT_{ij}$$

$\Delta EWT_{ij} \leftarrow EWT_{ij} - EWT_{ij}'$

$r_{ij} \leftarrow \Delta EWT_{ij}$

$\left(i^*, j^*\right) \leftarrow \arg\min_{i,j} \left\{ r_{i,j} \right\}$

$s_{i^*,j^*} \leftarrow s_{i^*,j^*} + 1$

End while

OUTPUT : s_{ij} **and** TC

4.2.2 Model-2 Decentralized

Decentralized version of Model-2 follows the same solution procedure with Model-2 but again separately as CW and LW are individual departments. Recall objective function of Model-2, to allocate stocks optimally subject to a waiting time constraint that is decided according to the management service performance target. As can be seen, there is not any budget to share in order to emphasize centralized-decentralized management style like Model-1. Therefore as individual departments would do, they will have different service targets. For this reason CW sets its stocks optimally according to its waiting time target. Also same procedure is applied to the LW with another waiting time target. Both CW and LW perform marginal analysis in order to allocate stock optimally, the item which gives the lower marginal value is chosen. Also Model-2 decentralized pseudo code is given below.

Initialize $s_{i0} \leftarrow 0$ **and** $\alpha \leftarrow 1$ $\qquad \forall\, i \in I$ **and** $j \in N, \alpha \leftarrow \{1, leadCW\}$

$TC \leftarrow \sum_{i \in I} \sum_{j \in N} c_i s_{i0}$

While $\Delta TC \langle 0$

For each $i \in I$ **and** $j \in N$

$s_{i0} \leftarrow s_{i0} + 1$

$TC' \leftarrow \sum_{i \in I} \sum_{j \in N} c_i s_{i0}$

$\Delta TC \leftarrow TC - TC'$

$r_{i0} \leftarrow \Delta TC$

$\left(i^*, j^*\right) \leftarrow \arg\min_{i,0} \left\{r_{i,0}\right\}$

$s_{i^*,0^*} \leftarrow s_{i^*,0^*} + 1$

End while

Initialize $WT_0^{\textbf{target}}$

$WT_0^{\textbf{target}} \leftarrow \alpha LeadCW$

$EWT_{i0} \leftarrow \frac{\lambda_{i0}}{\sum_{i \in I} \lambda_{i0}} EBO_{i0}$

While $EWT_{i0} \leq WT_0^{\textbf{target}}$

For each $i \in I$ **and** $j \in N$

$s_{i0} \leftarrow s_{i0} + 1$

$EWT_{i0}' \leftarrow \frac{\lambda_{i0}}{\sum_{i \in I} \lambda_{i0}} EBO_{i0}$

$\Delta EWT_{i0} \leftarrow EWT_{i0} - EWT_{i0}'$

$r_{i0} \leftarrow \Delta EWT_{i0}$

$\left(i^*, 0^*\right) \leftarrow \arg\min_{i,0} \left\{r_{i,0}\right\}$

$s_{i^*,0^*} \leftarrow s_{i^*,0^*} + 1$

End while

$\alpha \leftarrow \alpha + 0,05$

OUTPUT : s_{i0}

Initialize $s_{ij} \leftarrow 0$ $\qquad \forall\, i \in I$ **and** $j \in N$

$TC \leftarrow \sum_{i \in I} \left(\sum_{j \in N} c_i s_{ij} + \sum_{j \in N-0} c_j^{EM} \right)$

While $\Delta TC \langle 0$

For each $i \in I$ **and** $j \in N-0$

$$s_{ij} \leftarrow s_{ij} + 1$$

$$TC' \leftarrow \sum_{i \in I} \left(\sum_{j \in N} c_i s_{ij} + \sum_{j \in N-0} c_j^{EM} \right)$$

$$\Delta TC \leftarrow TC - TC'$$

$$r_{ij} \leftarrow \Delta TC$$

$$\left(i^*, j^*\right) \leftarrow \arg\min_{i,j} \left\{ r_{i,j} \right\}$$

$$s_{i^*,j^*} \leftarrow s_{i^*,j^*} + 1$$

End while

Initialize $WT_j^{\mathbf{target}}$

$$EWT_{ij} \leftarrow \frac{\lambda_{ij}}{\sum_{i \in I} \sum_{j \in N} \lambda_{ij}} EWT_{ij}$$

While $EWT_{ij} \leq WT_j^{\mathbf{target}}$

For each $i \in I$ **and** $j \in N-0$

$$s_{ij} \leftarrow s_{ij} + 1$$

$$EWT_{ij}' \leftarrow \frac{\lambda_{ij}}{\sum_{i \in I} \sum_{j \in N} \lambda_{ij}} EWT_{ij}$$

$$\Delta EWT_{ij} \leftarrow EWT_{ij} - EWT_{ij}'$$

$$r_{ij} \leftarrow \Delta EWT_{ij}$$

$$\left(i^*, j^*\right) \leftarrow \arg\min_{i,j} \left\{ r_{i,j} \right\}$$

$$s_{i^*,j^*} \leftarrow s_{i^*,j^*} + 1$$

End while

OUTPUT : s_{ij} **and** TC

5. RESULTS

Both centralized and decentralized solution graphics are given below. Detailed explanations are given relevant to each graphic. Both centralized and decentralized versions of the models are written in Microsoft Visual Basic Program. General view of both programs that written in VBA are given below.

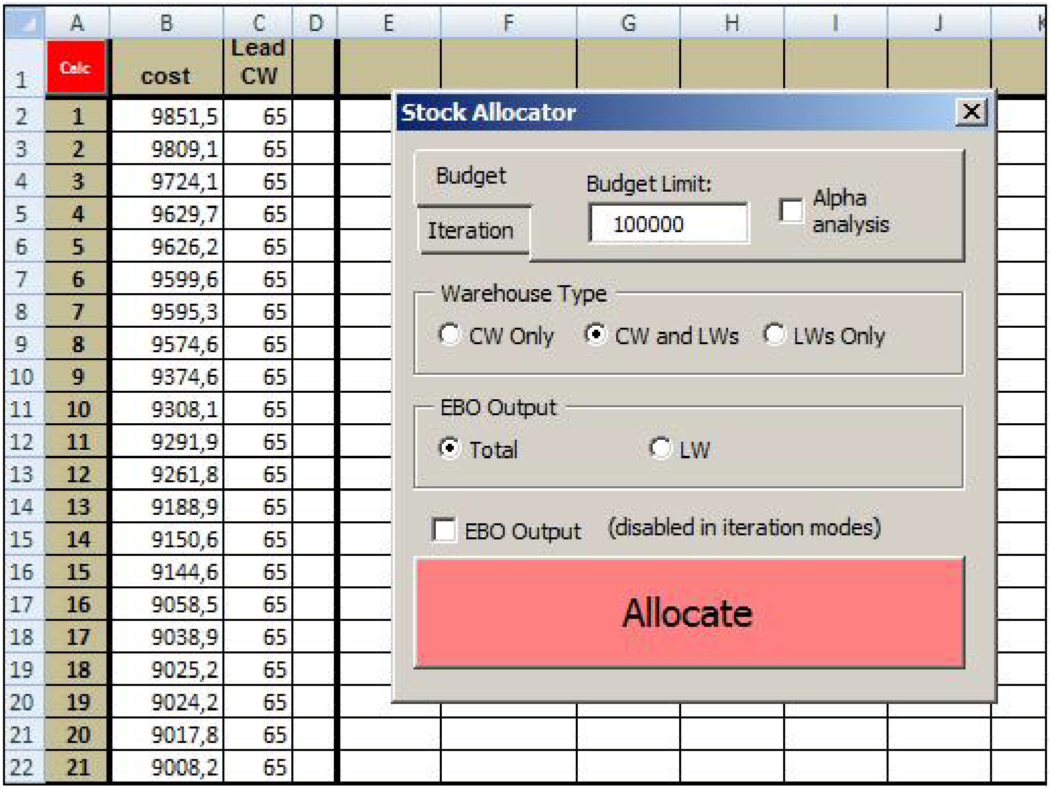

Figure 5.1 : Model-1 VBA view

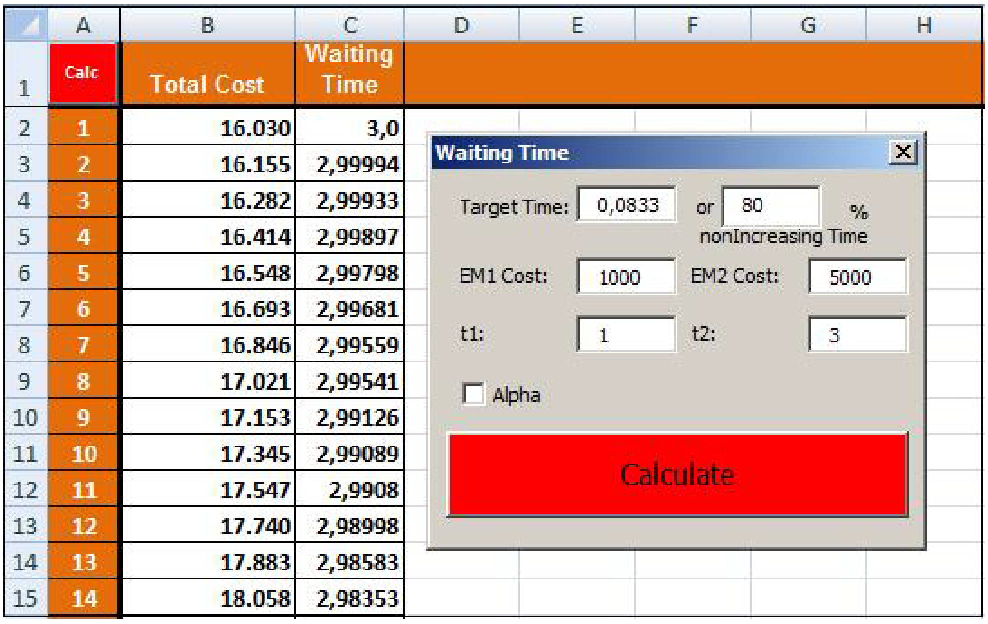

Figure 5.2 : Model-2 VBA view

5.1 EXPLANATION OF DATA USED

In this study 200 real life company spare part data is used. The company is a supplier of lithography systems for semiconductor computer chip manufacturers all over the world. The prices of spare parts change between 100 and 100,000 Euros, and their failure rates change between 0.0002 and 2 per year. As Sherbrooke (2004) said; spare parts tend to be expensive, and the demand at a LW for any particular item tends to be low. The same characteristics are observed in used data. In parallel with the same nature of parts, ten different random data sets are created. Each of the set contains 200 items. The random data set is generated in a way to follow the common intuition about spare parts that cheaper parts have higher failure rates. To support this argument, when company data examined is, it is seen that spare parts that are cheaper than 1500 Euros make up more than half of the total failure rate. By applying a similar logic ten random data are created such that the prices of spare parts are drawn from Uniform (1-10,000) Euro. The failure rates of spare parts are generated from different uniform distributions depending on the price of the spare part as explained in the following table. Average results of data sets are compared with company data results and their consistency has been observed.

Table 5.1 : Random data demand and cost setting procedure

Item price range, €	Demand per year (Failure rate per year)
1-2500	10 - 0.1
2500-5000	0.1 - 0.001
5000-7500	0.001 - 0.00001
7500-10,000	0.00001 - 0.000001

5.2 MODEL-1 CENTRALIZED AND DECENTRALIZED COMPARISON

In this section centralized and decentralized comparison will be made according to different inventory scenarios which will be explained in detail under each section. In order to compare such situations a greedy algorithm is used. As mentioned before CW and LWs optimal stock levels and expected backorders are calculated according to budget constraint. In greedy procedure, that budget constraint or say as inventory investment is shared between CW and LW. For simplicity, the share percentage that is used by one of the locations is called alpha. Alpha takes values 0 to 1. For computational simplicity, it is decided that when alpha is zero this implicates that the entire budget (total inventory investment) goes directly to CW, LW uses none. The exact opposite situation is applies for LW, when alpha value takes one entire budget is taken by LW. In middle values they share total budget according to this policy, like when alpha takes 0.4 this means, 40 percent of total investment is used by CW where LW uses 60 percent of it.

Centralized and decentralized solutions that are provided from a greedy algorithm will be shown in graphics. Result graphics are given as percentages instead of actual expected backorder levels. In each section company data and average random data set results will be shown, respectively.

5.2.1 CW-LW

In this section CW and only one LW are considered with different lead time values and budgets. Lead times are shifted according to the actual industrial data's lead time values. In Table 5.2 application scenarios are summarized.

Table 5.2 : CW-LW Scenario of Model-1

CW-LW Scenario				T_0 / t_j ; days
1	**Company Data**	**High budget**	**250,000 €**	**65/7**
				30/40
				7/65
		Low budget	**100,000 €**	**65/7**
				30/40
				7/65
2	**Average Random Data**	**High budget**	**50,000 €**	**65/7**
				30/40
				7/65
		Low budget	**10,000 €**	**65/7**
				30/40
				7/65

5.2.1.1 Company data results

As mentioned before real life company data is used in addition to random data sets. In Figure 5.3 given above, 65/7 replenishment lead times used for CW and LW, respectively. As it is seen in this situation up to 0.4 alpha values, centralized and decentralized model are consistent with each other. In order words, if centralized model's result is accepted as optimal value when CW takes 100 percent to 60 percent of budget, it shows nearly optimal trend.

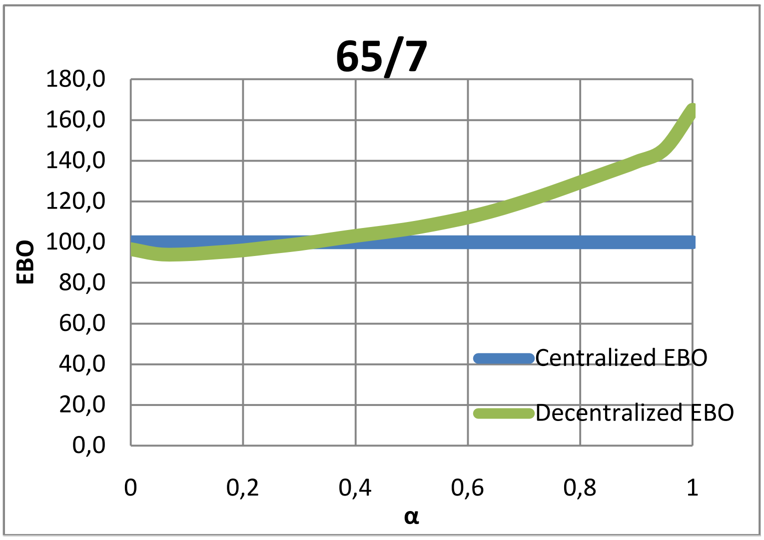

Figure 5.3 : Company data with 65/7 lead time/transportation time and high budget

When alpha exceed 50 percent where each of the location (CW and LW) shares equally allocated total budget, expected backorder values are increasing while LW is getting bigger share. In the point where alpha value takes one, this means LW uses entire budget. In Figure 5.3 results show that decentralized model deteriorates 64 percent than centralized version when LW uses all budget. Decentralized version's performance gradually decreases while LW budget share increases. This result reveals the insight that if the duration of resupply time for CW is long and the transportation time between CW and LW is short than allocating most of the budget to CW is preferable in a decentralized setting. If CW budget is low, then the total average resupply lead time for the LW is also long which generates high backorder levels even if the budget allocated for LW is high. Resupply lead time for CW plays a central role in the effect of different budget allocations. Because of long resupply lead time, in decentralized version where CW approximately takes entire budget 6 percent improvement can be observed. Low budget version of Figure 5.3 is given below as Figure 5.4.

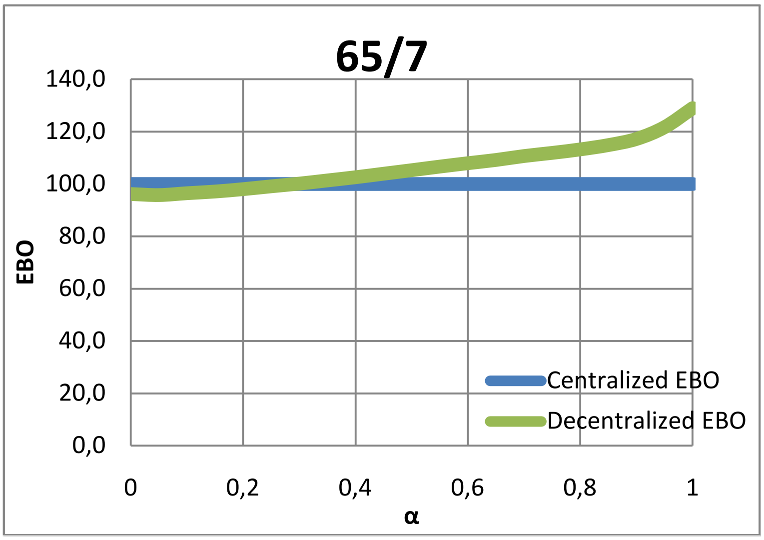

Figure 5.4 : Company data with 65/7 lead time/transportation time and low budget

Same trend with Figure 5.3 is observed when LW's budget share exceeds 50 percent of total allocated budget. Again, like preceding graphic because of long resupply lead time, in decentralized version where CW approximately takes entire budget 4 percent improvement can be observed.

In low budget version when alpha value gets one, decentralized version performance deteriorates 28 percent. Because of high inventory investment and higher share of LW Figure 5.3 performance decreases 64 percent which is clearly more than Figure 5.4. To simply say, when budget allocated increases, the budget share of LW increases with alpha process. When alpha takes nearly 1 which means LW has nearly 100 percent of total budget, CW almost has no budget to allocate stocks for this reason no matter how much stock LW takes, it fail to reduce expected backorders because of long resupply time of CW. The expected backorder increase due to decentralized approach is less when there is a lower budget for the multi-echelon system.

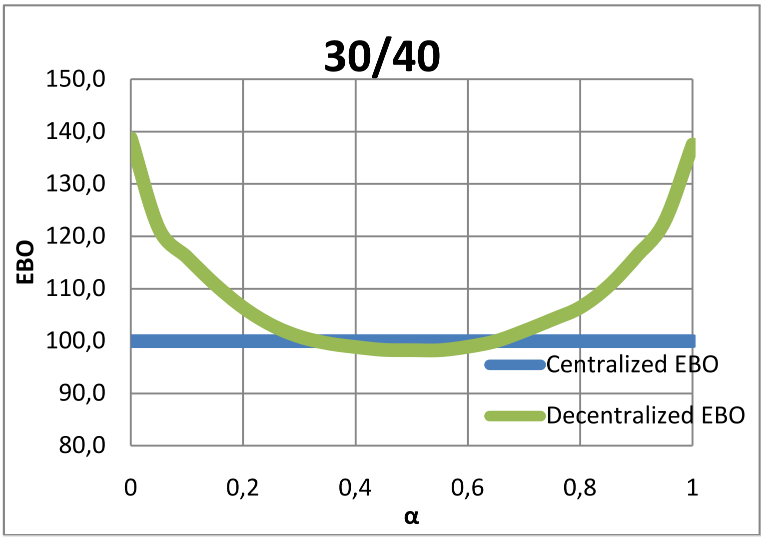

Figure 5.5 : Company data with 30/40 lead time/transportation time and high budget

In Figure 5.5 resupply lead time of CW is decreased where transportation time between CW and LW's is increased. It can be seen that with different lead time-transportation time combination previous decentralized trend has changed. When alpha value gets the limit values zero and one, it is clear that performance of the system decreases. Limit values refers to highest budget shares (When it is zero, CW's budget share 100 percent. When it is one, LW's budget share is 100 percent). It can be clearly observed that between 0.25-0.70 alpha values decentralized model nearly optimal, in fact 1.5 percent improvement of decentralized version can be seen between these alpha values. This gives the insight that the performance of the decentralized system is not very sensitive to the portion of budget allocated between CW and LW.

As stated in Figure 5.3 duration of replenishment lead times and transportation times between locations have direct effect on system's performance. Decentralized model's behavior is changing according to these durations. As can be seen in Figure 5.6, durations almost approximate unlike 65/7 version, for this reason decentralized model performance decrease in both limits alpha points where locations get highest budget shares.

This result shows that in a multi echelon system where decentralized management perspective is adopted for interdependent locations like CW and LW, when allocating total inventory investment resupply lead time of CW and transportation time between these locations must be taken into consideration. Once again in decentralized version high inventory investment alienated from optimal condition approximately 40 percent.

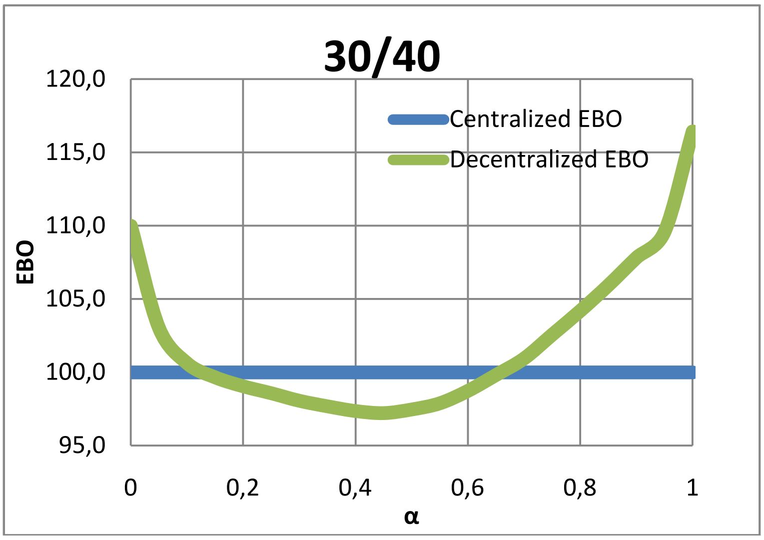

Figure 5.6 : Company data with 30/40 lead time/transportation time and low budget

Highest improvement that yields to 2.8 percent achieved in 0.45 alpha which refers to 55 percent budget share is used by CW while LW using 45 percent of it. Low budget version showed more close results to optimal than high budget version. Performance of decentralized low budget model decreases 15 percent considering high budget version.

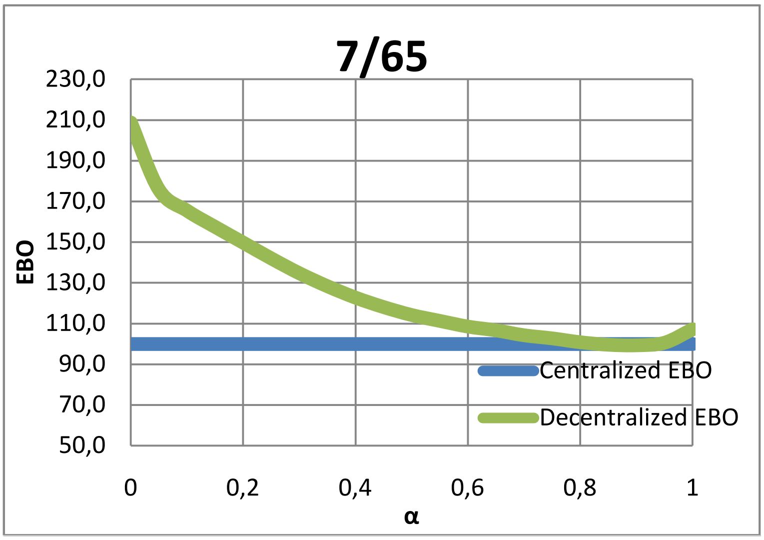

Figure 5.7 : Company data with 7/65 lead time/transportation time and high budget

When 7/65 replenishment lead-transportation time used for CW and LW, respectively, in Figure 5.7 decentralized trend shows that if LW has such a long lead time, it will be wise to allocate more stock to that LW. As can be seen when CW takes budget shares between 100 percent and 35 percent of total budget, decentralized system performance is much lower than centralized system. This means in such lead time situation where LW's lead time is extremely long, increasing LW's budget share is important because in order to decrease expected backorders LW needs to allocate more stocks. In the graphic between 0.75-1 alpha values decentralized model showed an optimal trend. Actually, Figure 5.7 has showed the exact opposite trend of Figure 5.3, which make sense because of the replenishment lead time of CW and transportation time between CW and LW.

Figure 5.8 shows same trend with Figure 5.7. In order to emphasize improvement in systems performance percentage display mode is chosen. However it is an inefficient mode to highlight high-low budget option. For this reason real results of graphics will be given in Appendix A.1 and A.2.

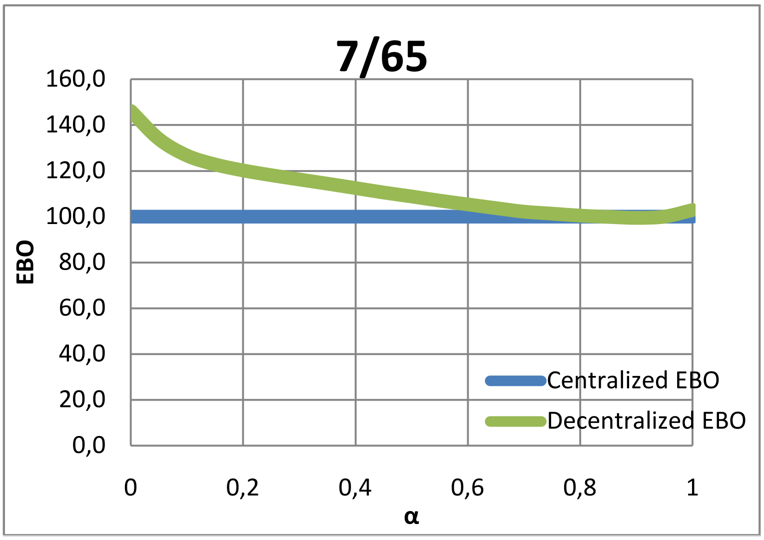

Figure 5.8 : Company data with 7/65 lead time/transportation time and low budget

5.2.1.2 Random data results

As mentioned before ten different data sets are created according to the nature of spare parts, low demand rates and dramatically high costs. As in section 0, random data result also examined one by one for CW-LW scenario of Model-1.

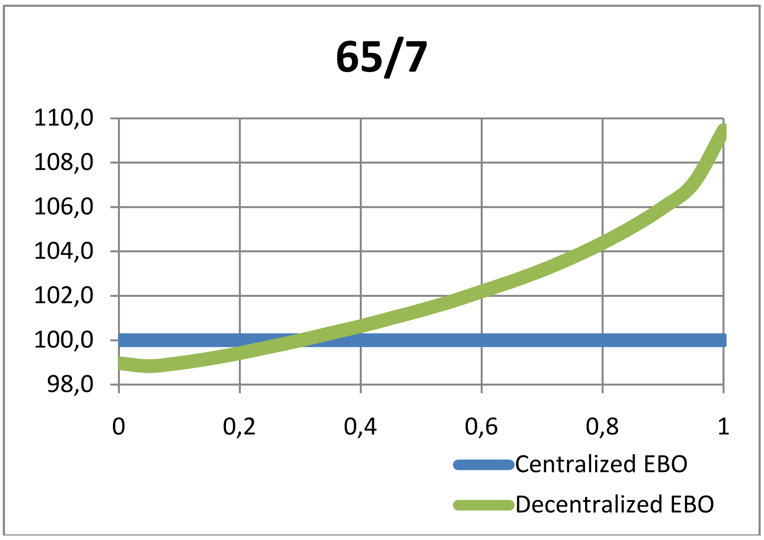

Figure 5.9 : Random data with 65/7 lead time/transportation time and high budget

Figure 5.9 has the same trend with the company data 65/7 version. In 0.3 alpha value that refers to 70 percent budget share for CW, centralized and decentralized model has the same performance. Even 1.5 percent of improvement can be seen in decentralized model at nearly zero alpha value. Because of the long lead time of the CW, model tries to allocate more stocks to CW in order to increase performance. As can be seen, when LW gets entire budget, expected backorder reaches the highest value.

Same trend can be seen in Figure 5.10, which lower inventory investment has been allocated. No matter how much is the total budget, as a consequence of 65/7 lead times, decentralized model performs same principal.

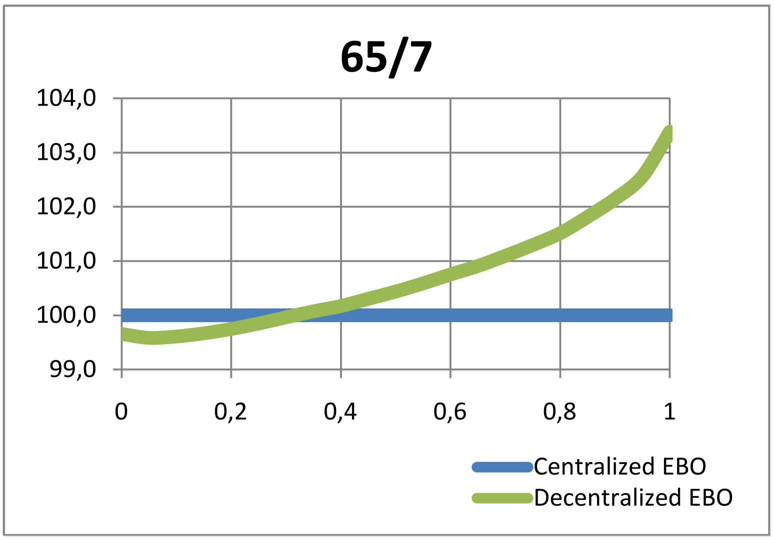

Figure 5.10 : Random data with 65/7 lead time/transportation time and low budget

Both Figure 5.11 and Figure 5.12 have same pattern in decentralized model with company data Figure 5.5 and Figure 5.6.

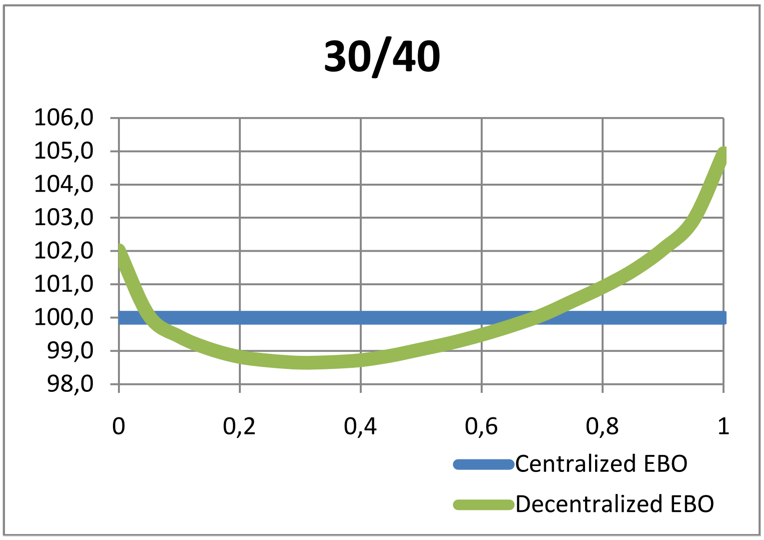

Figure 5.11 : Random data with 30/40 lead time/transportation time and high budget

Approximately, one percent performance improvement is provided. As before mentioned because of percentage display, decrease in expected backorders according to high-low budget allocation cannot be seen in graphic. However, it is well known that both decentralized and centralized inventory system's performance increases as expected backorders decreases with higher investment.

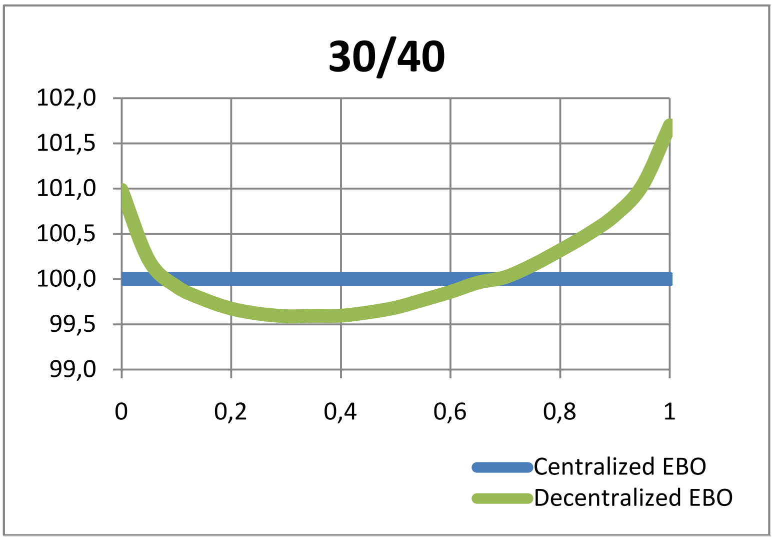

Figure 5.12 : Random data with 30/40 lead time/transportation time and low budget

As a result of long replenishment lead time of LW decentralized model tend to perform in same way both in company and random data.

In Figure 5.13 and Figure 5.14 as previously mentioned decentralized model tries to allocate stocks in LW in order to minimize expected backorders. In the point where LW has entire budget decentralized model catches optimal trend. Centralized model's behavior is accepted as optimal behavior as explained in previous sections, theoretically it has been proved that multi-echelon models performs better than single-echelon adaptation models. In Figure 5.13, approximately one percent improvement has been observed in decentralized model.

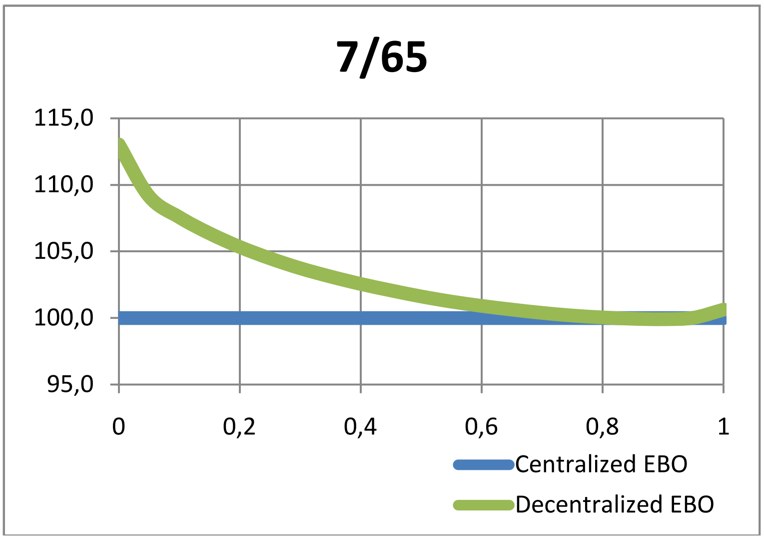

Figure 5.13 : Random data with 7/65 lead time/transportation time and high budget

High budget version of 7/65, CW replenishment lead time/ transportation time between CW and LW, that is given below nearly 13 percent decrease in expected backorder level is achieved where Figure 5.14, expected backorder level decreases only 5 percent. The reason of the difference is amount of budget that has been allocated to system. When system has high amount of budget, it has opportunity to decrease backorders. However, because of the low budget allocation, model that is given in Figure 5.14 was able to enhance system performance only 5 percent.

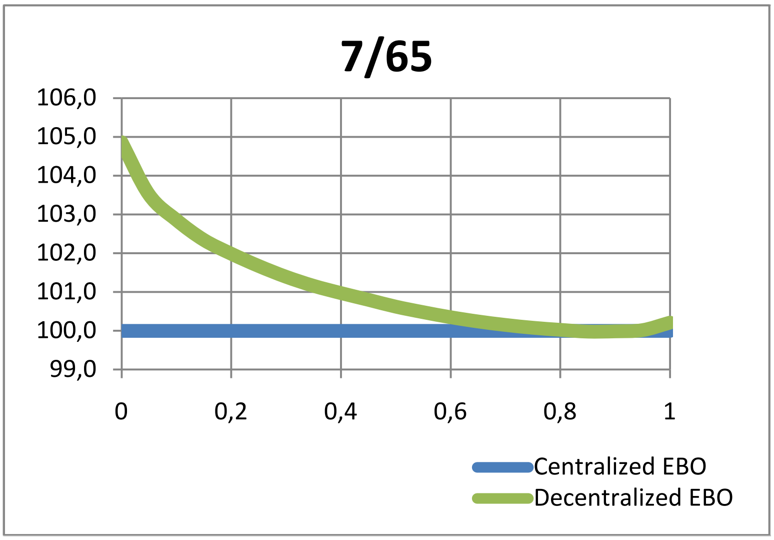

Figure 5.14 : Random data with 7/65 lead time/transportation time and low budget

5.2.2 CW-2LW

In this section CW and two identical LWs are considered with different lead time values and budgets. The reason of this scenario is to seek for effects on CW where its demand doubled. As explained in solution procedure CW demand combines from total demand of LWs. When there are multiple LWs in inventory system, this can cause pooling in CW which refers to holding more stock in CW in order to meet LW's orders.

LWs with identical demand rates and lead times are determined. As mentioned before replenishment lead time and transportation time between CW and LW are shifted according to the actual industrial data's lead time values. In Table 5.3 application scenarios are summarized.

In previous section, it is observed that random data results are consistent with real life company data. For this reason random data graphics are not given in this section, they can be seen in Appendix B.1 and B.2.

Table 5.3 : CW-2LW Scenario of Model-1

CW-2LW Scenario				$T_0 / t_j / t_j$; days
1	Company Data	High budget	250,000 €	65/7/7
				30/40/40
				7/65/65
		Low budget	100,000 €	65/7/7
				30/40/40
				7/65/65
2	Average Random Data	High budget	50,000 €	65/7/7
				30/40/40
				7/65/65
		Low budget	10,000 €	65/7/7
				30/40/40
				7/65/65

5.2.2.1 Company data results

Recall the same 65/7 situation with former graphics. Long lead time of CW induces expected delay of CW which influence directly LW's lead time as well as expected backorders in LW. That's why model tends to give higher budget share to the CW instead of two LWs. As a consequence of sum of two LW's demand, CW's total demand has doubled; this is a non-negligible fact that effects decentralized model in Figure 5.15 and Figure 5.16. For this reason model catches optimal conditions between 0 and 0.2 alpha values where CW budgets has the 100 percent and 80 percent of the total investment. Only a small amount of service improvement of decentralized model achieved in 0.05 alpha value in both graphic. Performance of decentralized model deteriorates from optimal condition about 0.4 alpha value where LWs' budget share begins to increase. As a result of long CW lead time highest decrease in performance is achieved in 1 alpha value where LWs get entire budget.

Figure 5.15 shows same trend with Figure 5.3 where 65/7 lead time/transportation scenario in CW-LW is also used. Both in high and low budget graphics of CW-2LW scenario because of two LWs, expected backorders doubled compared to CW-LW. This increase can be observed form exact numerical graphics. Total expected backorder decrease in high budget version is higher than low budgets version.

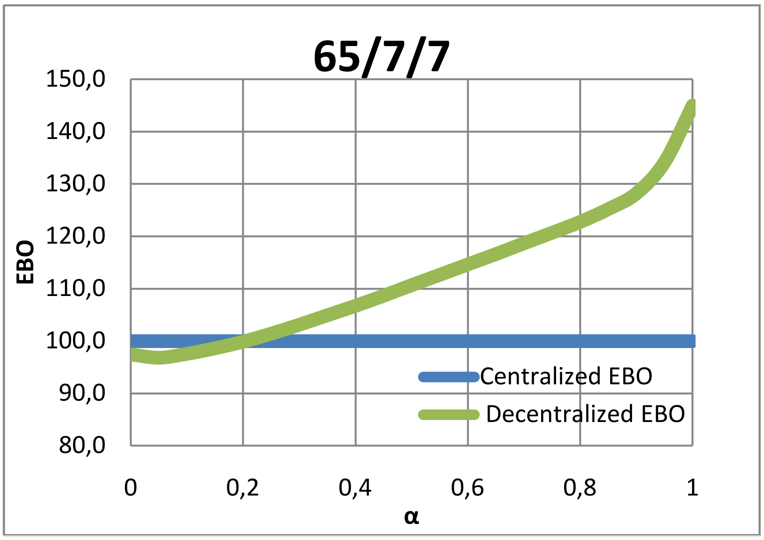

Figure 5.15 : Company data with 65/7/7 lead time/transportation time and high budget

Figure 5.16 results are consistent with Figure 5.4 where low budget version of same CW lead time/ transportation time between CW and LW is used.

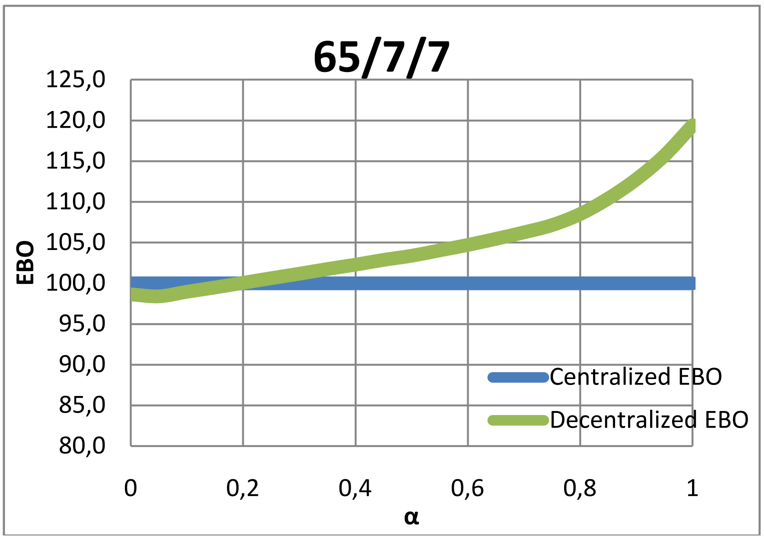

Figure 5.16 : Company data with 65/7/7 lead time/transportation time and low budget

In Figure 5.17, between 0.25 and 0.60 alpha values wide range optimality is achieved. The reason of this optimality with different budget shares is replenishment lead times are almost approximate. Three percent improvement in decentralized model has been observed.

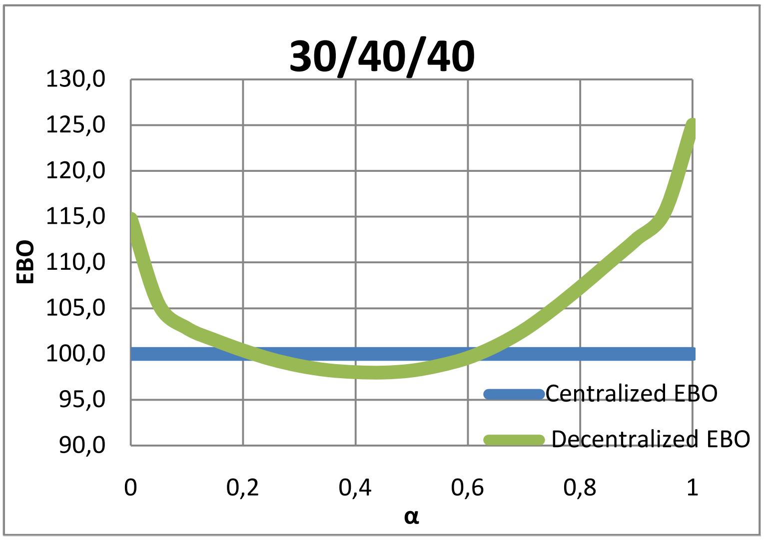

Figure 5.17 : Company data with 30/40/40 lead time/transportation time and high budget

In addition, Figure 5.18 nearly 4.5 percent improvement achieved in decentralized model. High budget version is decreased expected backorders approximately 15 percent where low budget allocated model only 1.5 percent. Recall that, high budget allocated decentralized models are enhancing systems performance in wide range until they have reached to the optimal alpha point. As mentioned before because of budget constraint low budget inventory systems are not able to enhance their performance dramatically.

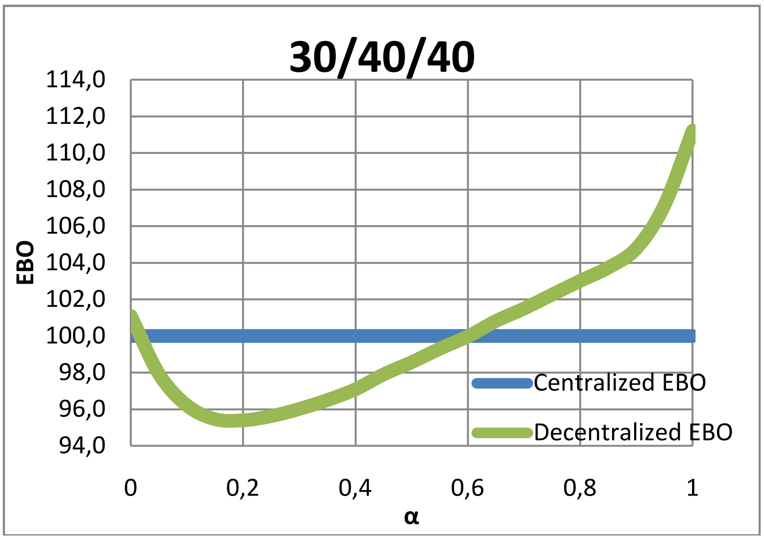

Figure 5.18 : Company data with 30/40/40 lead time/transportation time and low budget

Since two identical LW's is utilized, CW's total demand is increased, to be more precise it is doubled. Expected backorders values approximately doubled in CW-2LW scenarios compares to CW-LW scenarios, which can be seen in numeric graphics in Appendix B.1. Decentralized model still tends to allocate higher budget share to the LWs because of lead time of CW and transportation time. Only 20 percent of total budget will be enough for LWs in order to catch optimal condition, which is accepted as centralized model solution where CW uses 80 percent of total budget. Necessity of high budget share originates from long lead time and demand of LWs.

In Figure 5.19 replenishment lead time of CW is short compared to transportation time between LW and CW. As a result of this decentralized model behaved optimal in 0.8 alpha value where LWs get 80 percent of total inventory investment. Decentralized model performance deteriorates approximately 60 percent from optimal condition say as centralized model when CW gets entire budget. Direct effects of resupply lead time and transportation time between locations are also displayed in this graphic.

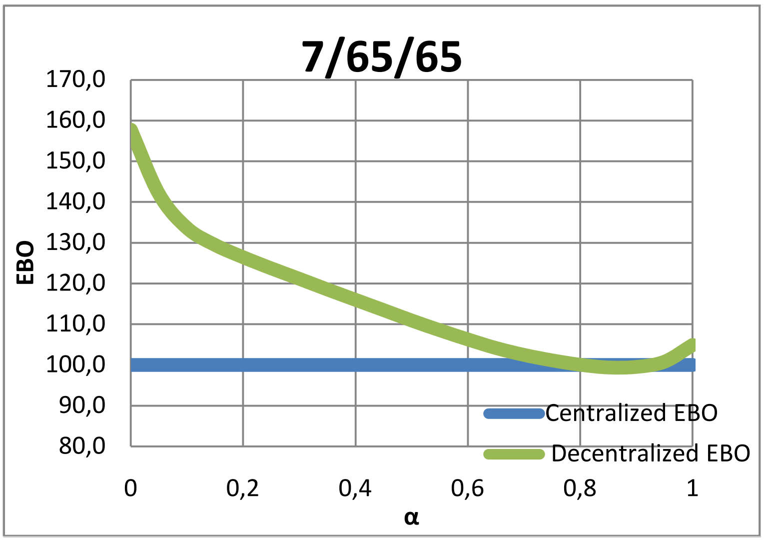

Figure 5.19 : Company data with 7/65/65 lead time/transportation time and high budget

In Figure 5.20 same trend with Figure 5.19 can be seen. In low budget version decentralized model performance in zero alpha value decreases 20 percent where high budget version decreases approximately 60 percent.

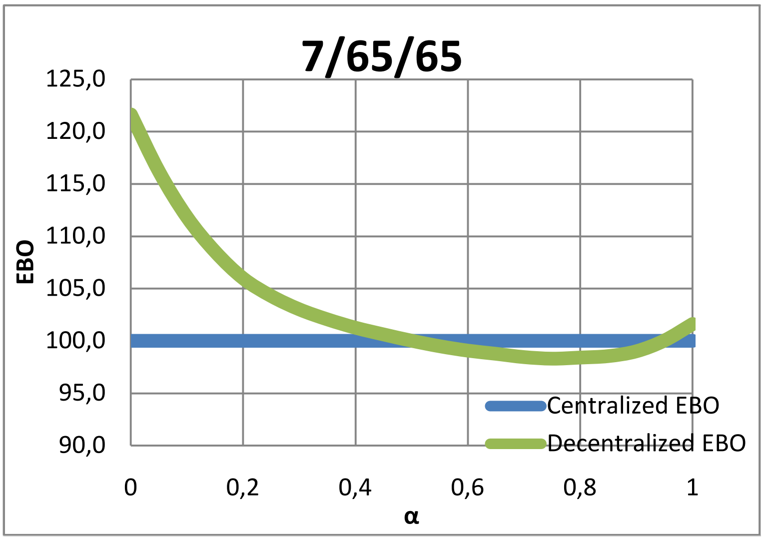

Figure 5.20 : Company data with 7/65/65 lead time/transportation time and low budget

Also CW-2LW scenario applied to random data set which is combined from average value of ten separate random data sets in order to provide consistency. Similar results consistent with company data results that are presented in preceding sections have been observed. In order to avoid repetition, graphics are not analyzed individually. They are given in Appendix B.2.

5.3 MODEL-2 CENTRALIZED AND DECENTRALIZED COMPARISON

In this section centralized and decentralized comparison will be made by adopting Model-2's principals. Unlike Model-1, this model allocate stock levels according to a given service performance target, waiting time, while minimizing total inventory investment. Since single-echelon adaptation model and multi-echelon model cannot be compared from different budget share allocations, different greedy algorithm is designed.

Major purpose of this thesis is to compare inventory management styles in multi-echelon systems. In practice, when a company adopts Model-2 decentralized version as an inventory control policy, each inventory locations of this company will have different service performance targets. Because they prefer to act as independent departments. Since Model-2 utilizes waiting time target, both CW and LWs can have same or different waiting time targets. Having same or different target is not important in such situation. The important point is that not having a jointly adopted target and not cooperating to achieve it.

The locations that are interested in this study, CW and LWs are tending to act independently while they are dependent because of various reasons as mentioned earlier. However inventory investment is a bounding factor that pushes companies to model their inventories as a centralized system. Misallocation and waste of excessive inventory investment can cause serious damages to the company.

In order to represent centralized-decentralized management system in Model-2, a greedy algorithm is designed. Algorithm calculates both CW and LW as an individual department with different waiting time targets. But still mutual interaction preserved in algorithm.

Centralized management in which CW and LW are managed together in order to achieve a particular waiting time target is examined versus decentralized management style in which both CW and LW has different waiting time targets.

For simplicity, alpha value that refers to different waiting time targets of CW is adopted. LW’s waiting time target will not change during the calculations. In this model for example, 0.2 alpha value refer to a waiting time target of CW that is 20 percent of CW’s lead replenishment time, 1 alpha value represent actual lead replenishment time of CW. Graphics are drawn total system inventory cost versus alpha values that represents different CW waiting time targets.

Solutions that are provided from a greedy algorithm are shown in graphics as decentralized solutions. Result graphics of two hours waiting time target of LW with company data and random data are given as percentages instead of actual total cost values. Since consistency is observed in solutions, other scenarios are given as combined graphics that displays actual cost values. In Appendix C.1, 2, 3 and 4 individual numerical graphics can be found.

In Model-2 CW-LW scenario is considered with company data 1,2 and 4 hours waiting time target of LW. Because of computational difficulties random data only considered with 2 hours waiting time target and 65/7 (CW lead time/ transportation time CW to LW) scenario. In greedy solutions as mentioned before alpha values are representing different waiting time target's of CW which are determined according to certain percentages of replenishment lead time of CW. In Table 5.4 applied scenarios are given. Target waiting times, replenishment lead time values of CW and transportation time between CW and LW are given for Model-2 applications can be seen in the table.

Table 5.4 : CW-LW of Model-2

CW-LW Scenario			T_0 / t_j ; days
1	Company Data	1 hours waiting time target	65/7
			50/22
			45/27
			40/32
		2 hours waiting time target	65/7
			50/22
			45/27
			40/32
		4 hours waiting time target	65/7
			50/22
			45/27
			40/32
2	Random data	2 hours waiting time target	65/7

In Figure 5.21 centralized vs. decentralized graphic for 2 hours waiting time target of LW with 65/7 (resupply time of CW / transportation time between CW and LW) is given. Unlike Model-1, this model minimizes inventory cost and allocates stocks subject to a given waiting time target. In greedy solution say as decentralized solution, each alpha point represents waiting time target of CW which acts as an independent department. Comparisons will be made on whether having only one system target as in centralized solution or having individual different targets.

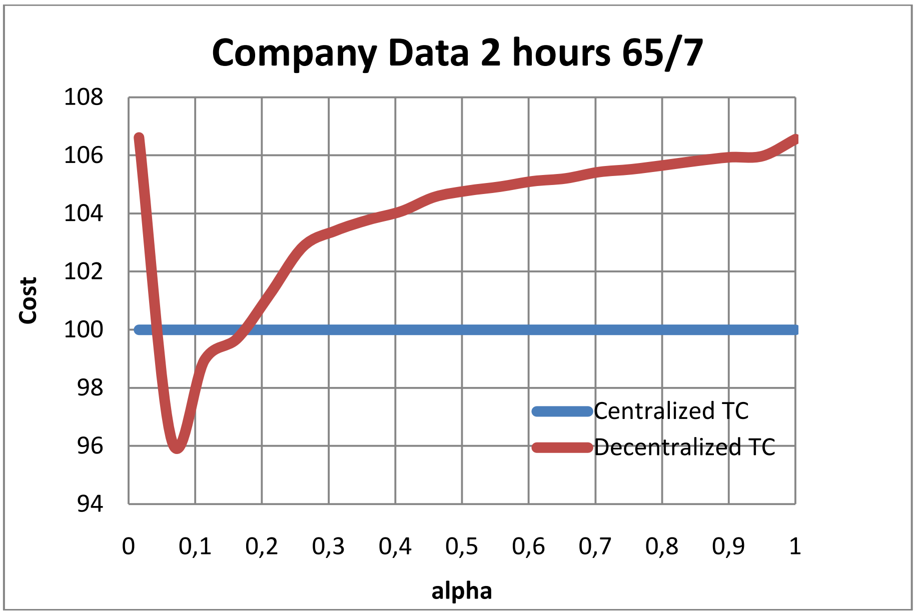

Figure 5.21 : Company data with 2 hours waiting time target 65/7 CW replenishment lead time/transportation time

Between 0 and 0.06 alpha values where CW has lower waiting time target, decentralized model's performance is 6.5 percent is lower than centralized model's performance. Because of lower target time and long replenishment lead time of CW decentralized model tends to allocate more stocks. Therefore decentralized version starts with highest total cost. The highest cost is achieved in alpha where CW's waiting time target nearly 1.3 days (approximately 32 hours). Then in 0.06 alpha where CW's target time approximately 4 days (94 hours), decentralized system shows 4 percent improvement considering centralized model as the optimal solution. After 0.16 alpha value performance gradually decreases in decentralized solution (total cost gradually increases). It is difficult to determine interrelation between LW and CW targets from graphics.

However, effects of duration of lead time CW and transportation time between CW and LW on system's behavior can be observed as in Model-1 results. Decentralized solutions behaves similar in both models, they tend to allocate more stocks in the location that can cause longer delay.

In Figure 5.22 random data shows same trend as company data. Again same results implies to this graphic. Duration of replenishment lead time of CW and short waiting time target of CW effects decentralized system behavior. Similar trend with Figure 5.21 is observed.

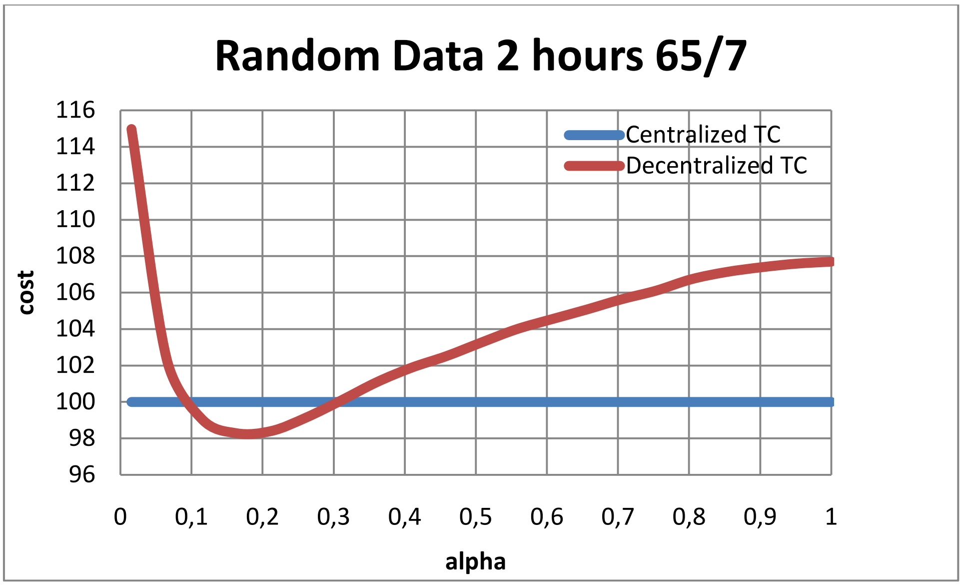

Figure 5.22 : Random data with 2 hours waiting time target 65/7 CW replenishment lead time/transportation time

Unlike Model-1 results, it is difficult to interpret Model-2 results because of the structure of model. Greedy solution that is applied in Model-2 decentralized version shows reasonable trends in limit alpha points (zero alpha and 1 alpha points), however in middle alpha points is effortful to comment on system's behaviors.

As stated before other solutions are given in combined graphics which includes different CW replenishment lead time and transportation combinations. In Figure 5.23, one hour waiting time target for LW is adopted with 65/7, 50/22, 45/27 and 40/32 replenishment lead time (CW's) and transportation time (between CW and LW) combinations.

In each combination decentralized model's behavior is consistent with each other. The highest improvement in decentralized model (single-echelon adaptation model) is achieved in 65/7 scenario where CW tends to allocate more stocks because of the expected delay. Expected delay of CW can be higher between 0.06 and 0.16 alpha points because of long duration of resupply time and short waiting time target. Short waiting time target in other words short response time to customers, all by itself is a challenge for companies. These types of targets represent high service quality and they are difficult to achieve because of various relevant or irrelevant reasons in the company. So, the reason of decentralized solutions behavior between 0-0.6 alpha values can be explained as the efforts that are made for achieving short service performance targets.

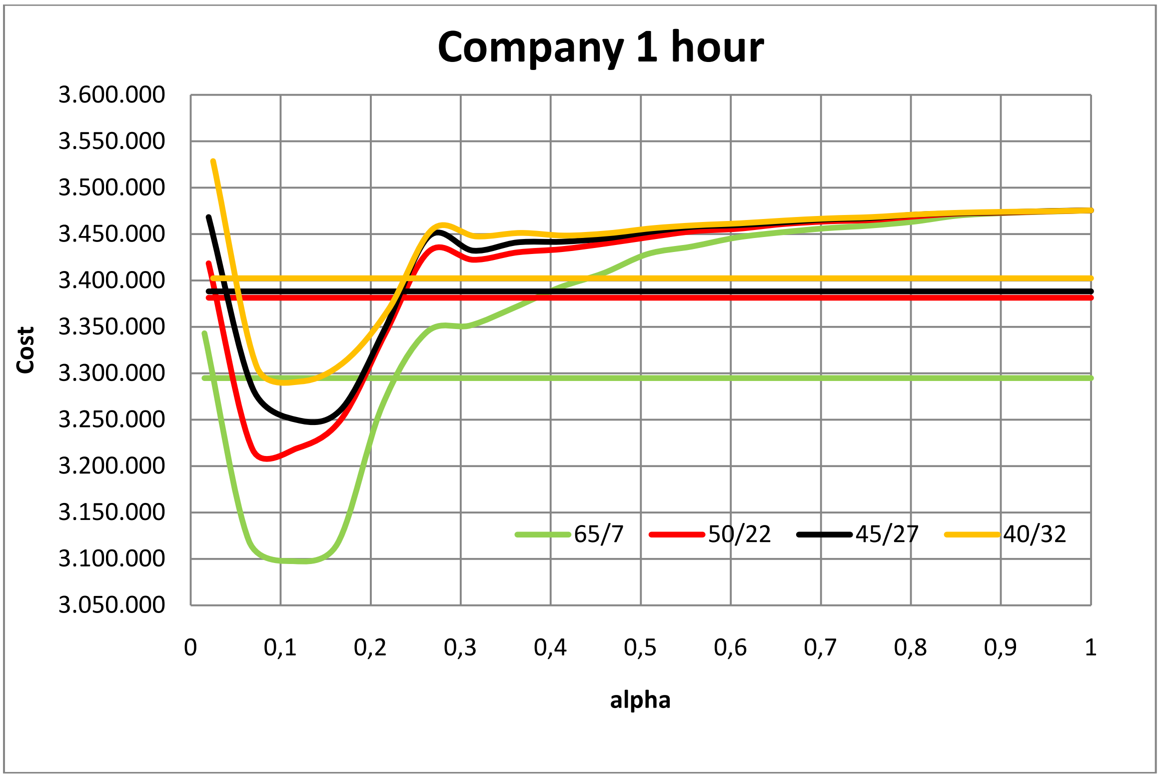

Figure 5.23 : Company data with 1 hour waiting time target with different replenishment lead time/transportation time combinations

After 0.3 alpha point decentralized models' costs are gradually increasing. Because CW's waiting time target is gradually approximating to its own lead time and decentralized models tends to allocate more stocks in order to decrease LW's waiting time.

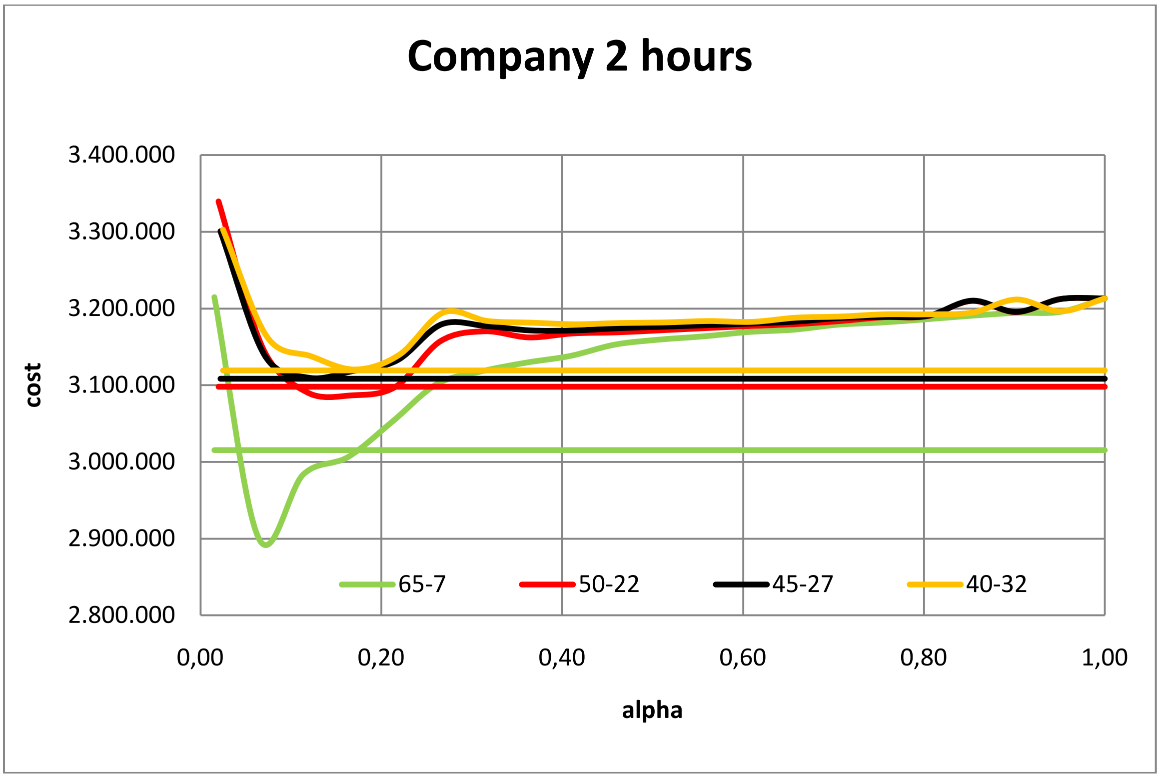

Figure 5.24 : Company data with 2 hour waiting time target with different replenishment lead time/transportation time combinations

Two hours waiting time target is applied to the company data, results can be seen in Figure 5.24. Trends of decentralized models are similar with preceding graphic. Centralized solutions are better than decentralized solutions after alpha value of 0.2.

As mentioned before, when CW has low waiting time target decentralized model tends to allocate more stock in order to that achieve target. That behavior leads high costs in each combination (replenishment lead time of CW/transportation time between CW and LW) that can be seen firstly in graphic. Decentralized model showed increase in total cost where CW has lower waiting time targets. Between alpha values of 0.6 and 11, decentralized model of 65/7 performs well compared to centralized model.

In Figure 5.25 four hours waiting time target is used. Except 65/7 decentralized solution, other decentralized solutions performances deteriorate compared to centralized solutions. Only in 65/7 combination has small amount of service improvement can be observed.

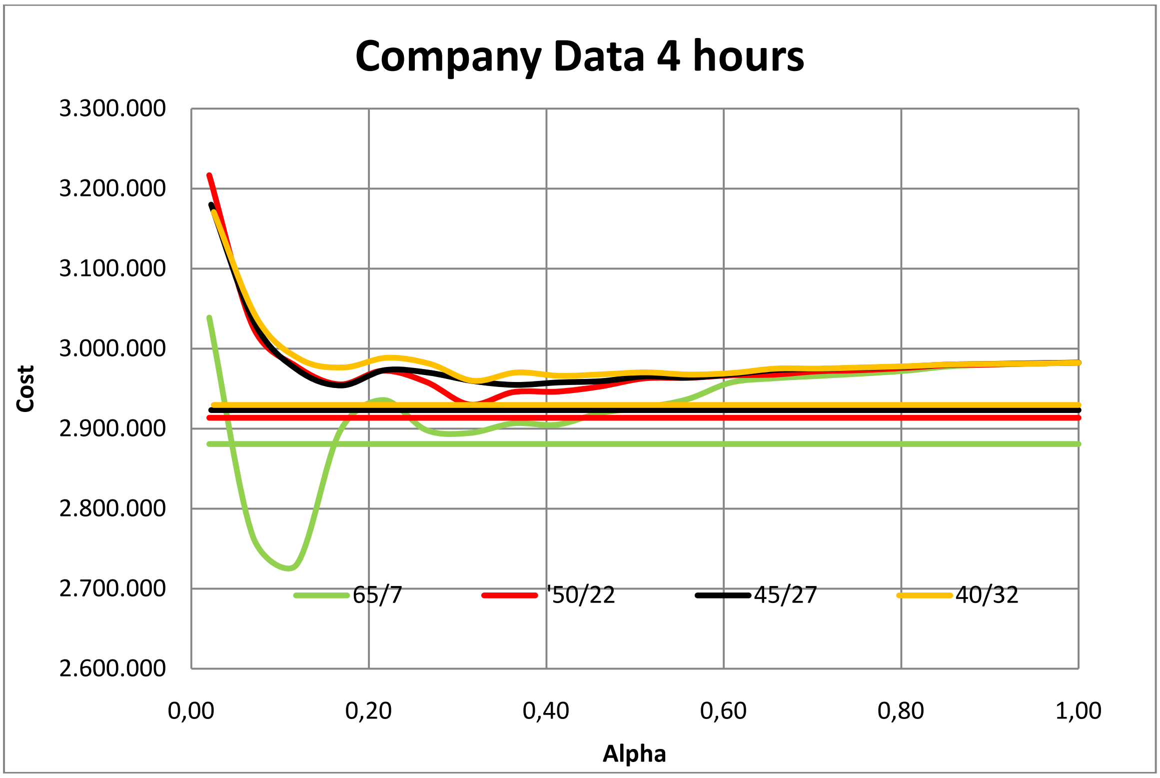

Figure 5.25 : Company data with 4 hour waiting time target with different replenishment lead time/transportation time combinations

As can be seen in preceding graphics, centralized solutions of each combination are performed better than decentralized solutions. Only small amount of improvements are achieved in some cases but it is difficult to interpret a general behavior for the system according to these solutions.

It is very complicated to set different targets for interdependent locations like CW and LW while system's behavior effects directly from durations of CW lead time and transportation time. Model-2 is a complex model to apply individual service performance targets. Because of computational challenges and interpretation difficulties Model-2 can be unfavorable.

6. CONCLUSION

In multi-echelon spare part distribution systems each location has its own role in the supply chain network. Such as, CW and LW have different roles in the network. CW supposed to “fill the pipeline” and support the LW (Hausman & Erkip, 1994, p.493). Holding same stocks with high holding costs in different locations say as CW and LW is not a desirable option in the company because of heavy holding costs.

Major concern of this study is to analyze centralized and decentralized management behavior in multi-echelon systems in order to avoid waste and allocation of excessive amount of inventory investments. Two models are presented in order to analyze centralized and decentralized management perspectives.

Result of comparisons showed that lead replenishment time of CW and transportation time of CW to LWs have direct effects on decentralized model behavior in both examined models. Model’s behavior changes according to duration. In order to increase system performance models allocate more stocks considering delays.

Also high amounts of investments needed in decentralized models in order to increase service levels. In limited budget versions, decentralized models are failed to decrease expected backorders. However in low budget limited versions decentralized models displayed close behavior to centralized models. Numerical graphics showed that total amount of increase in high budget allocated models is higher than low budget models.

The characteristics of spare parts are drawn attention to the importance of multi-echelon models. It is unnecessary to hold stocks of expensive items that have very low demand rates in every location in resupply system. These stocking decisions must be made for all locations by a centralized management. The amount of savings from low-demanded high cost items can be very high.

In solution graphics where centralized versus decentralized behavior of the system are shown, in some points decentralized model performance increased approximately 3 percent considering centralized model as optimal point. For further researches, according to system characteristics a general rule can be provided, while determining optimal system behavior.

Decentralized management (single-echelon models adaptations) style is preferable by companies because of the managerial and organizational simplicity. Generally, companies make trade-offs in this kind of situations, some can ignore considerable savings from multi-echelon system control for managerial effortlessness.

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APPENDICES

Appendix A.1 Model-1 CW-LW company data graphics

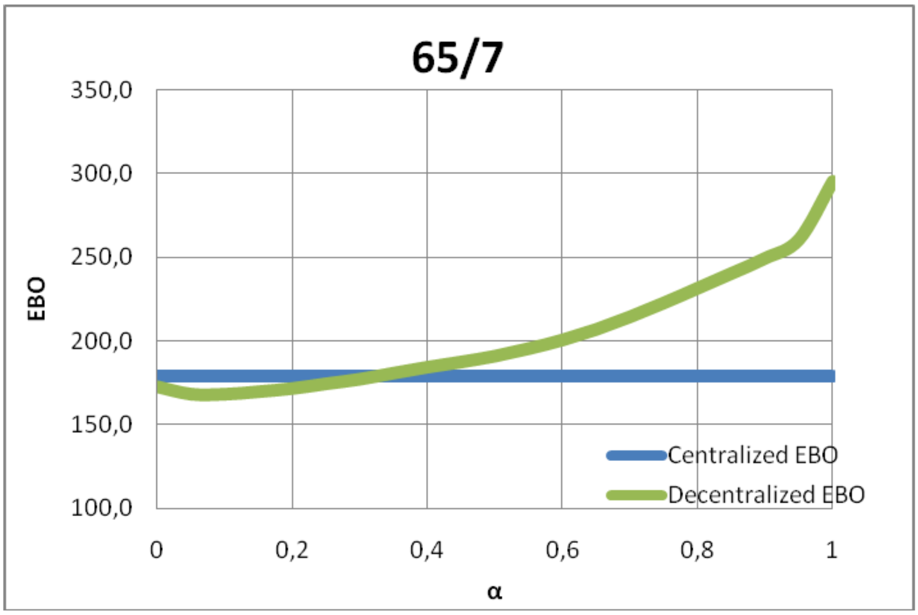

Figure A.1 : Company data 65/7 CW resupply lead time/ transportation time with 250,000 € budget

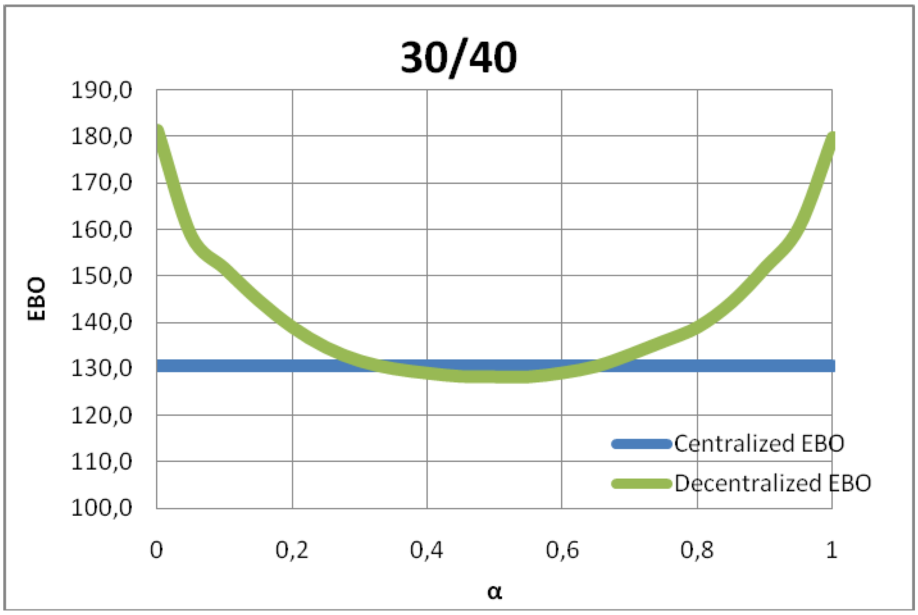

Figure A.2 : Company data 30/40 CW resupply lead time/ transportation time 250,.000 € budget

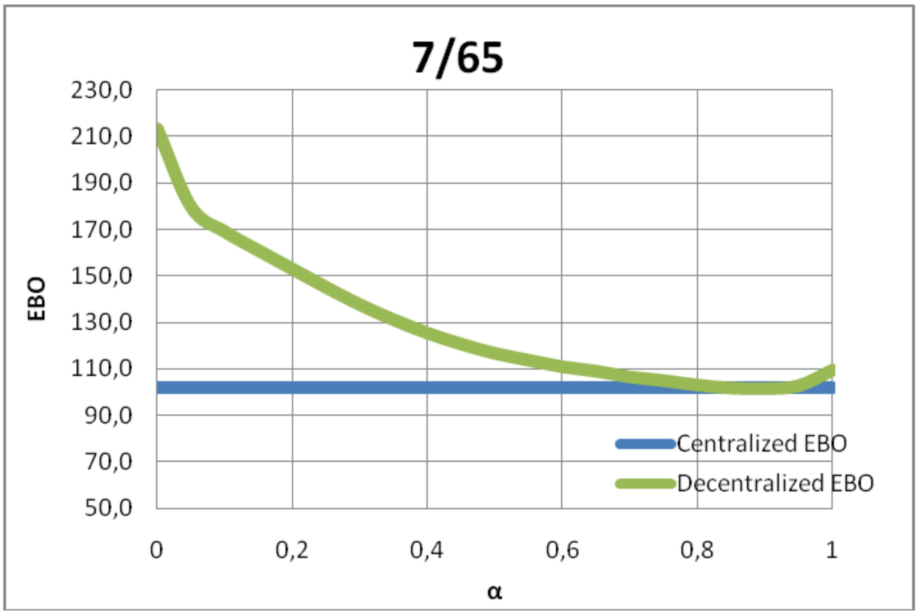

Figure A.3 : Company data 7/65 CW resupply lead time/ transportation time with 250,000 € budget

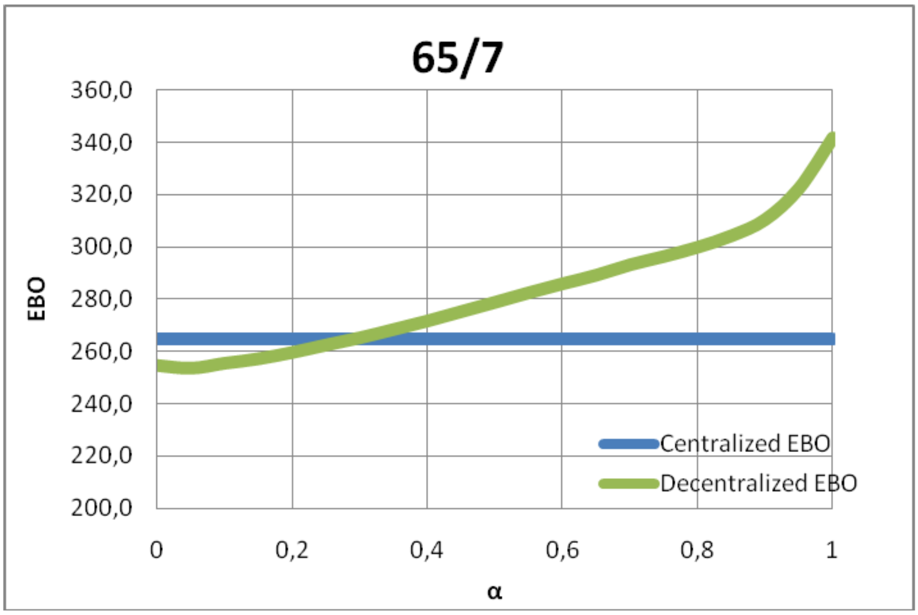

Figure A.4 : Company data 65/7 CW resupply lead time/ transportation time with 100,000 € budget

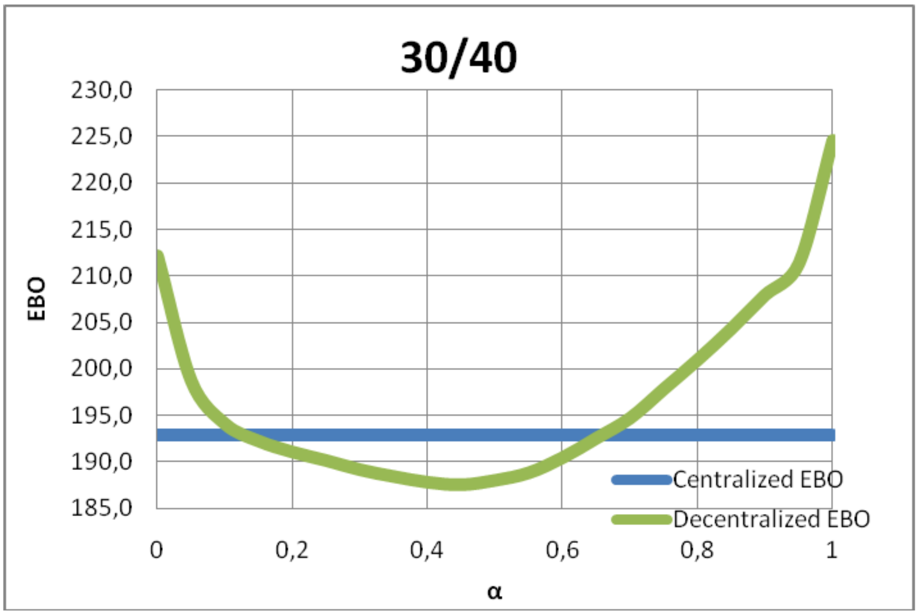

Figure A.5 : Company data 30/40 lead times CW resupply lead time/ transportation time 100,000 € budget

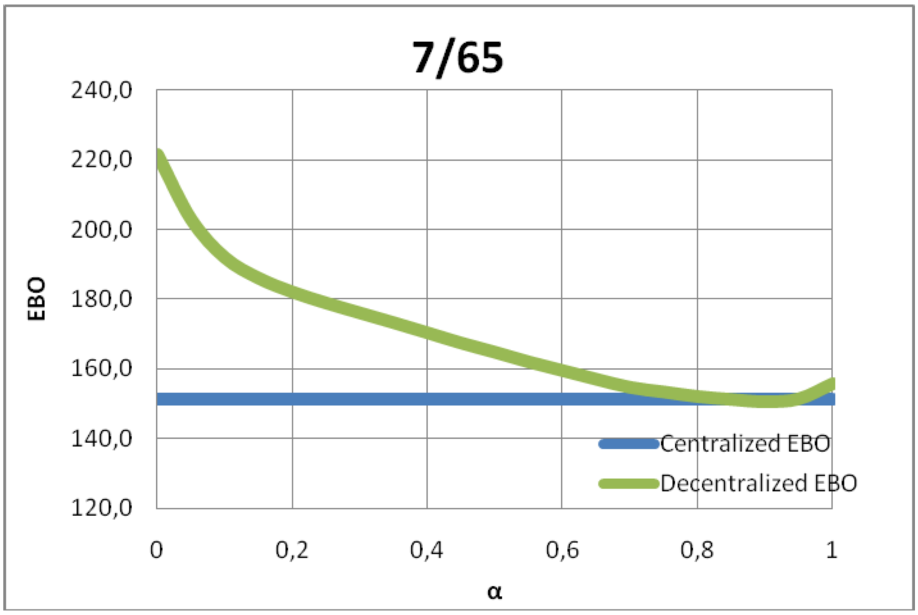

Figure A.6 : Company data 7/65 CW resupply lead time/ transportation time with 100,000 € budget

Appendix A.2 Model-1 CW-LW random data graphics

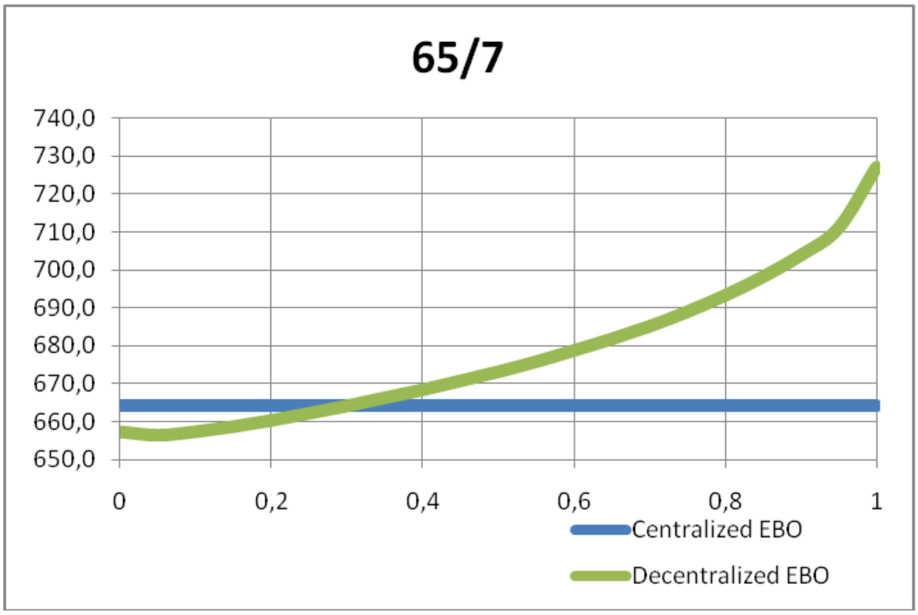

Figure A.7 : Random data 65/7 CW resupply lead time/ transportation time with 50,000 € budget

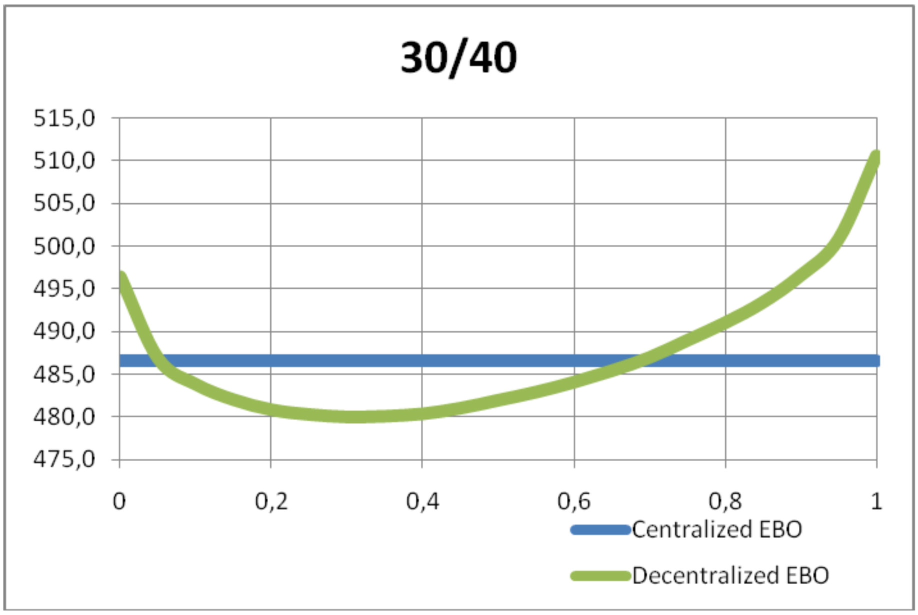

Figure A.8 : Random data 30/40 CW resupply lead time/ transportation time with 50,000 € budget

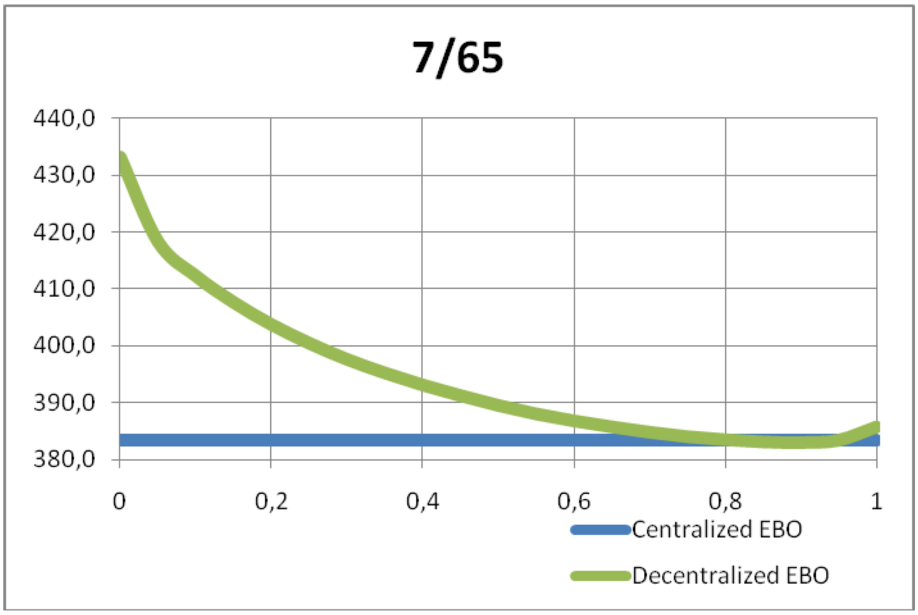

Figure A.9 : Random data 7/65 CW resupply lead time/ transportation time with 50,000 € budget

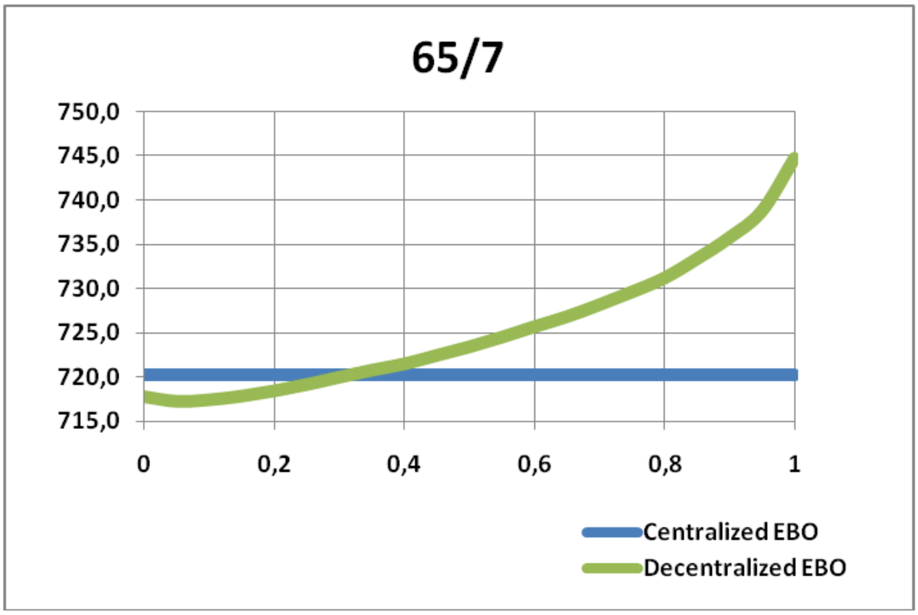

Figure A.10 : Random data 65/7 CW resupply lead time/ transportation time with 10,000 € budget

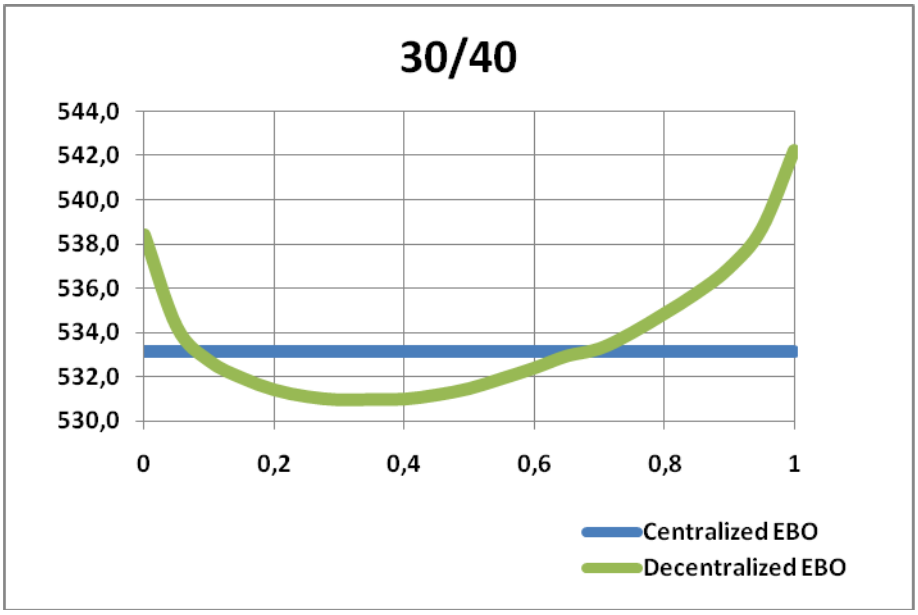

Figure A.11 : Random data 30/40 CW resupply lead time/ transportation time with 10,000 € budget

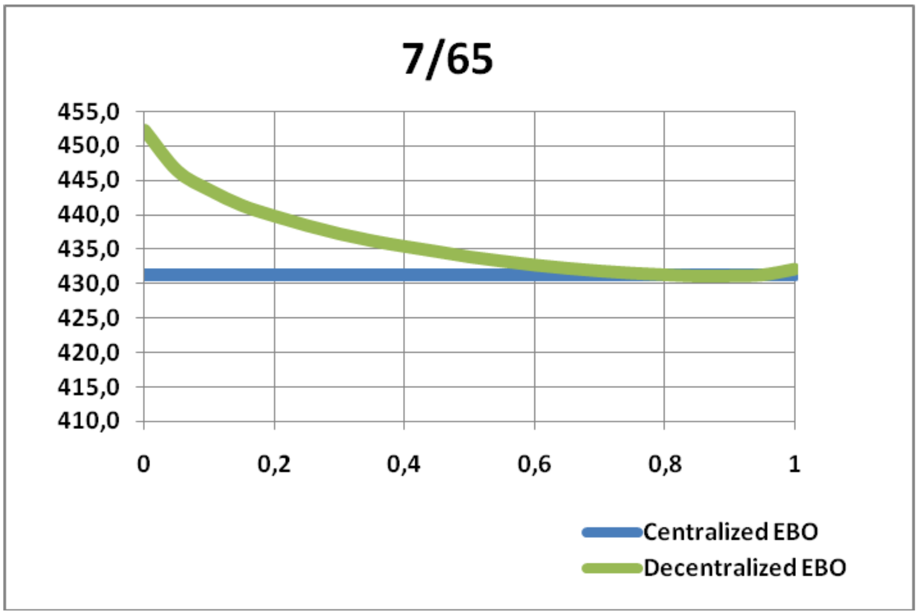

Figure A.12 : Random data 7/65 CW resupply lead time/ transportation time with 10,000 € budget

Appendix B.2 Model-1 CW-2LW company data graphics

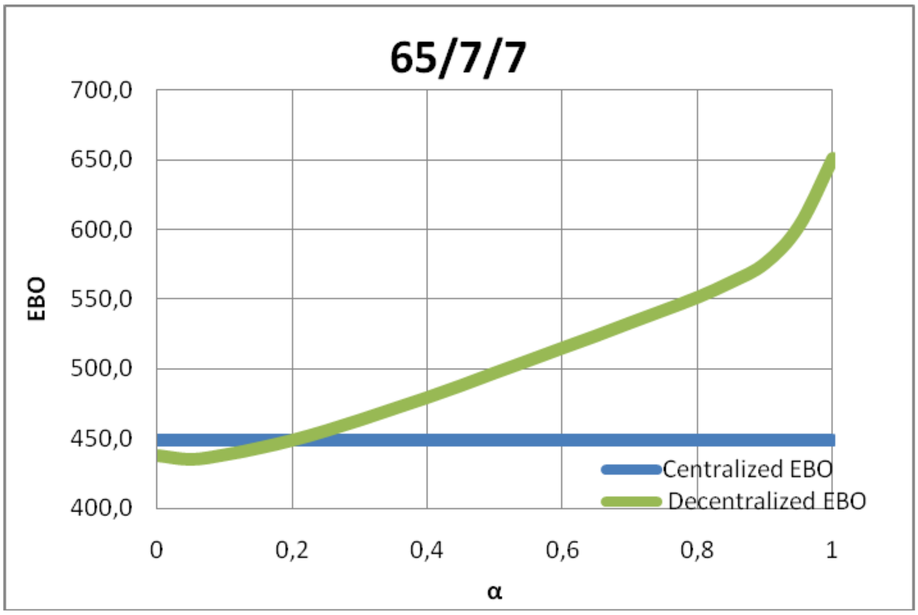

Figure B.1 : Company data 65/7/7 CW resupply lead time/ transportation time with 250,000 € budget

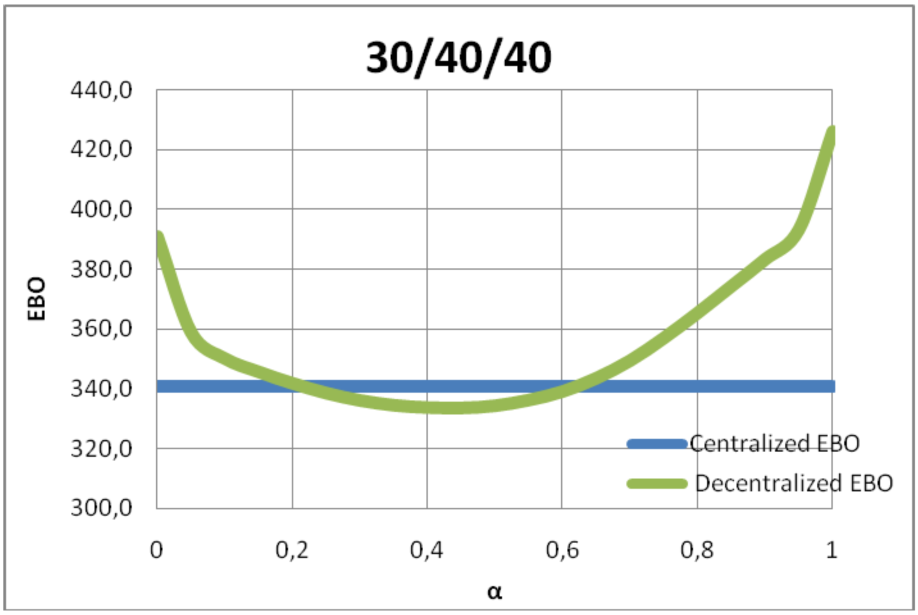

Figure B.2 : Company data 30/40/40 CW resupply lead time/ transportation time with 250,000 € budget

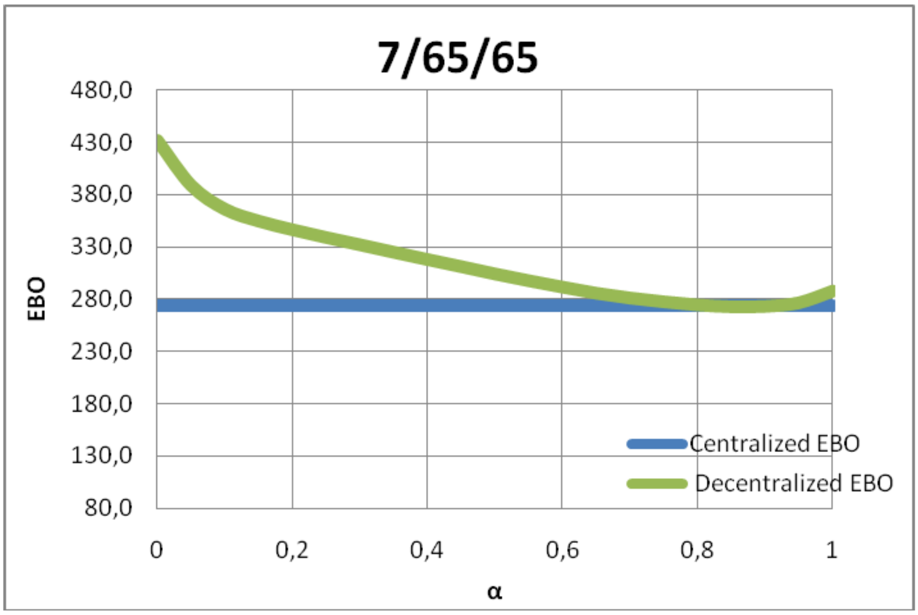

Figure B.3 : Company data 7/65/65 CW resupply lead time/ transportation time with 250,000 € budget

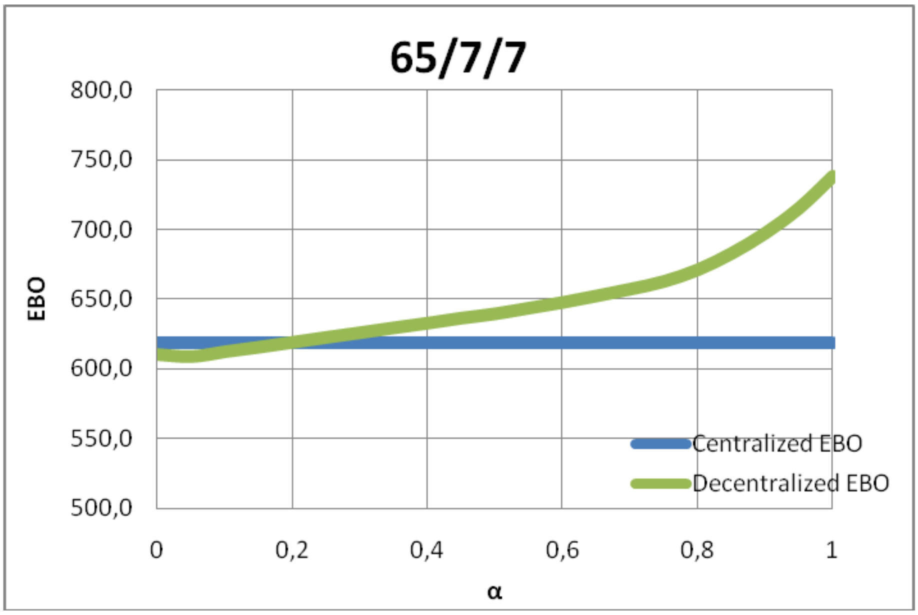

Figure B.4 : Company data 65/7/7 CW resupply lead time/ transportation time with 100,000 € budget

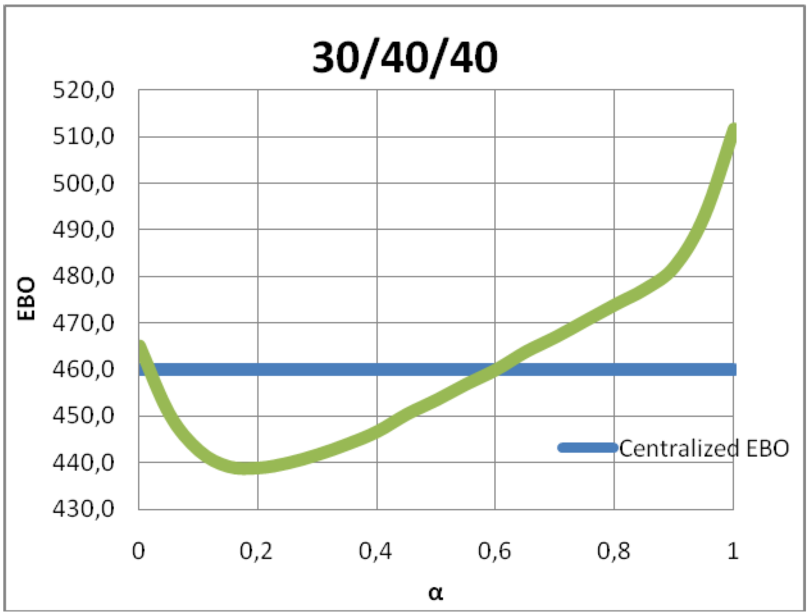

Figure B.5 : Company data 30/40/40 CW resupply lead time/ transportation time with 100,000 € budget

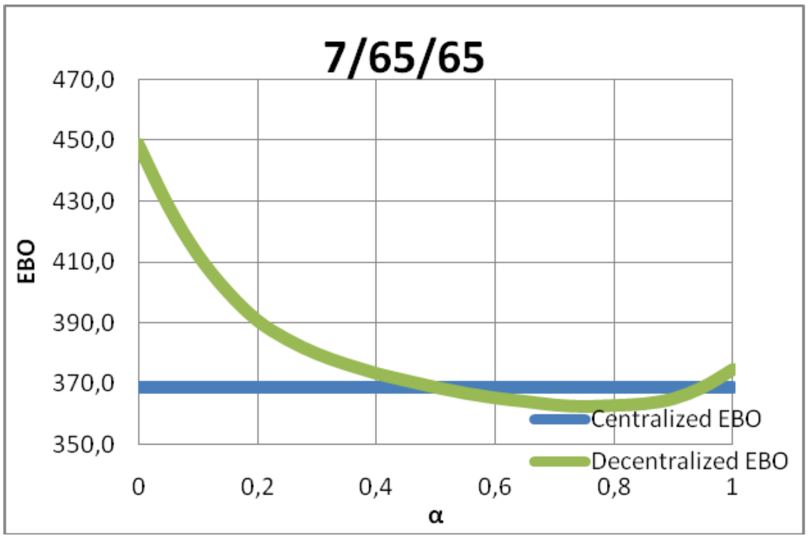

Figure B.6 : Company data 7/65/65 CW resupply lead time/ transportation time with 100,000 € budget

Appendix B.2 Model-1 CW/2LW random data graphics

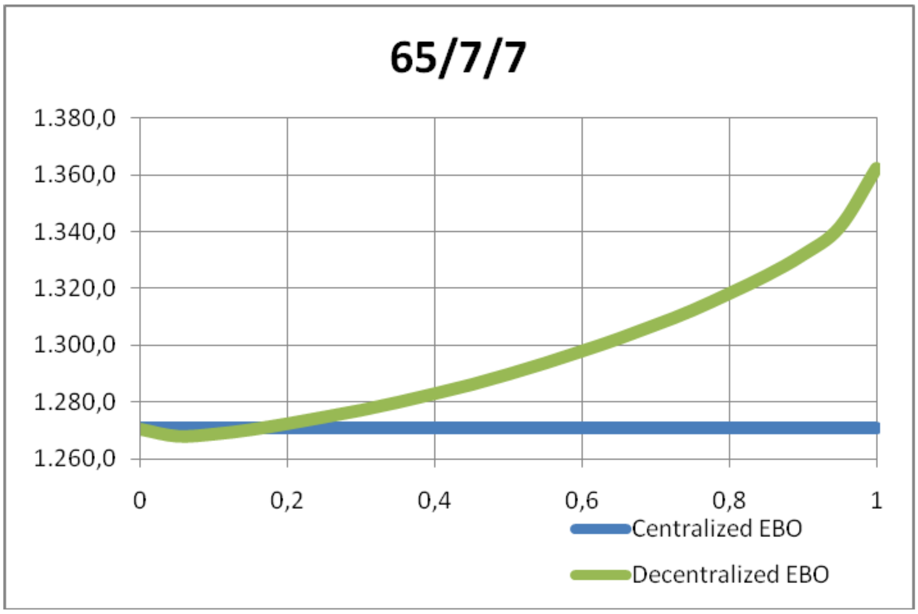

Figure B.7 : Random data 65/7/7 CW resupply lead time/ transportation time with 50,000 € budget

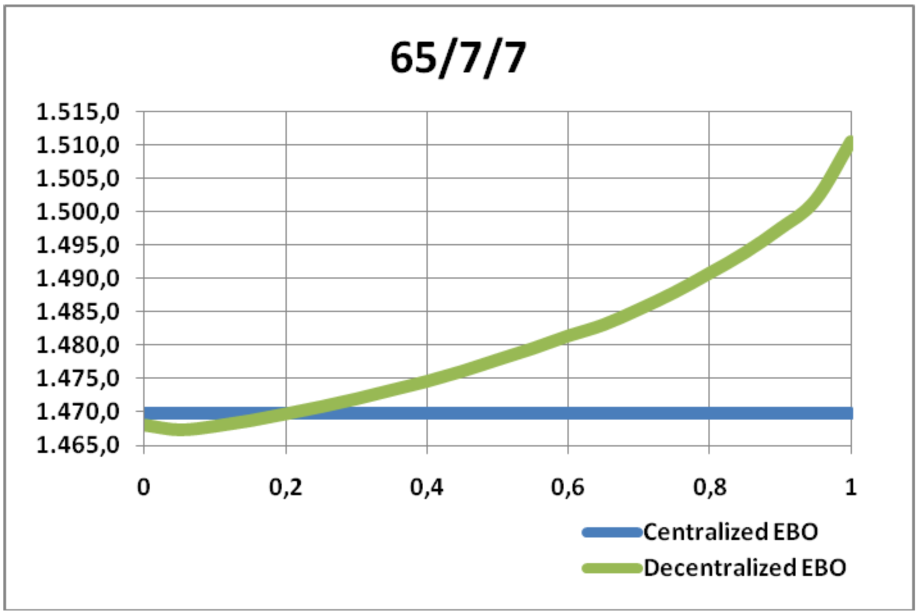

Figure B.8 : Random data 65/7/7 CW resupply lead time/ transportation time with 10,000 € budget

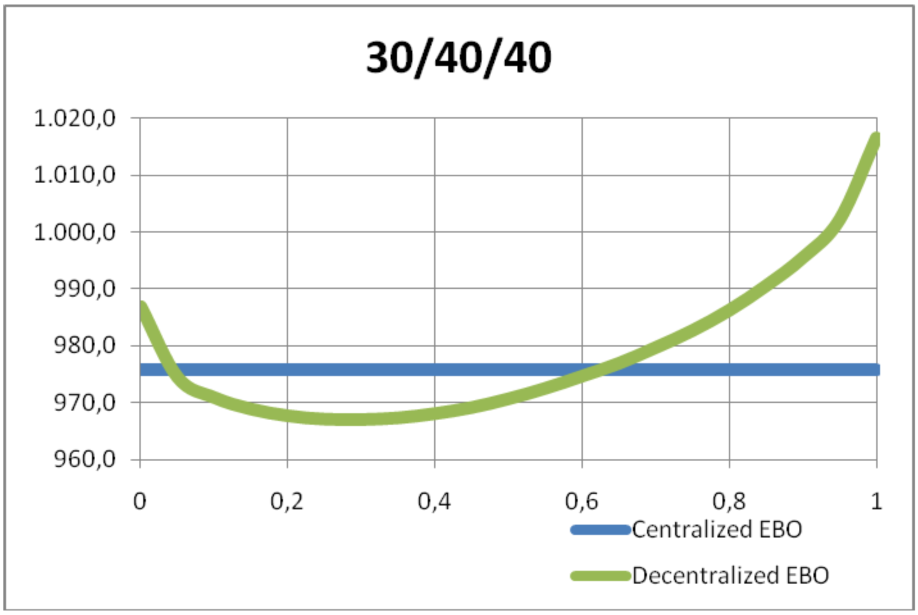

Figure B.9 : Random data 30/40/40 CW resupply lead time/ transportation time with 50,000 € budget

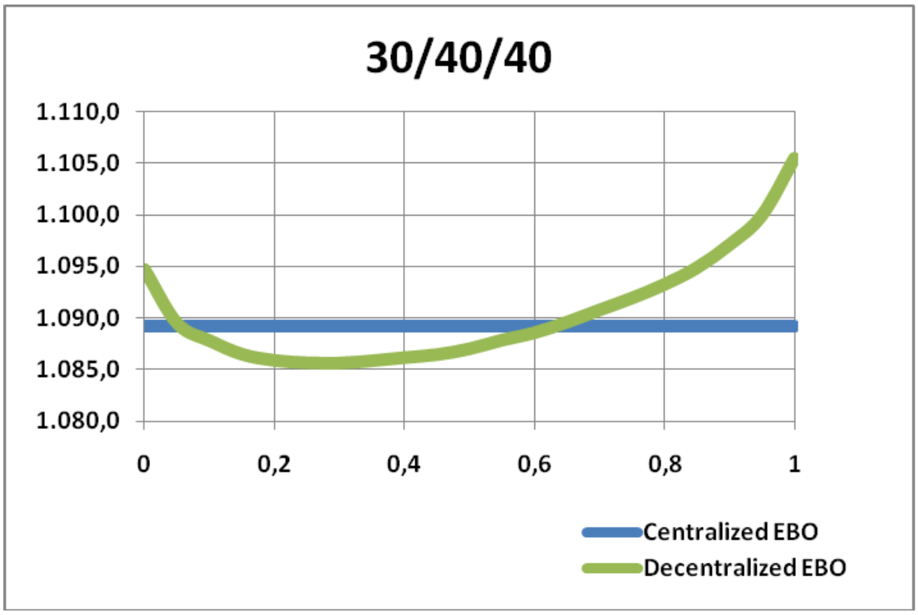

Figure B.10 : Random data 30/40/40 CW resupply lead time/ transportation time with 10,000 € budget

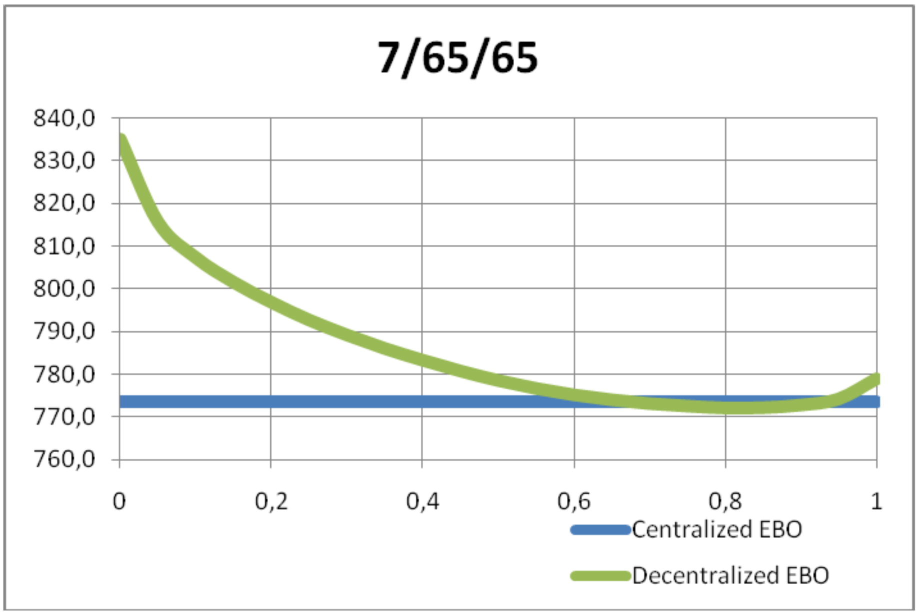

Figure B.11 : Random data 7/65/65 CW resupply lead time/ transportation time with 50,000 € budget

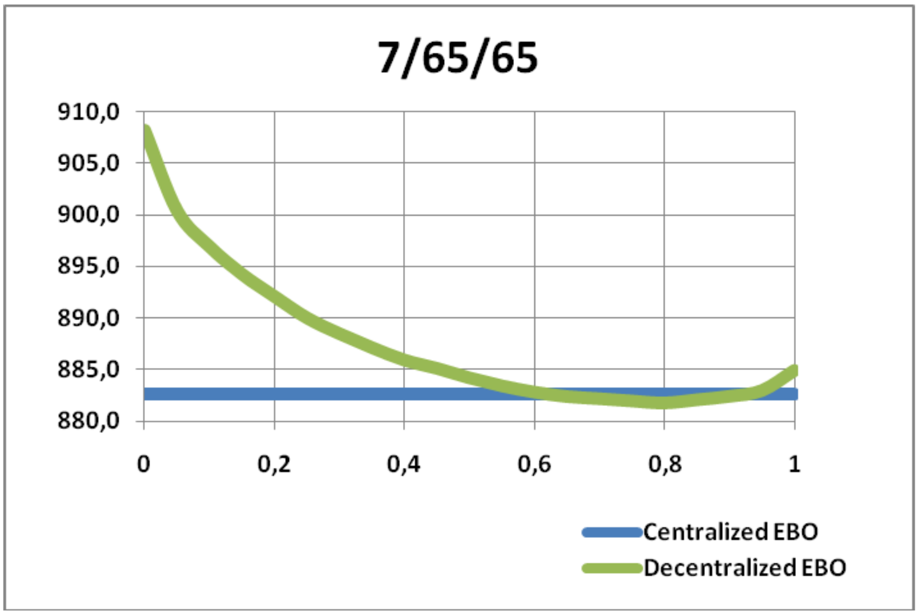

Figure B.12 : Random data 7/65/65 CW resupply lead time/ transportation time with 10,000 € budget

Appendix C.1 Model-2 random data 2 hours graphic

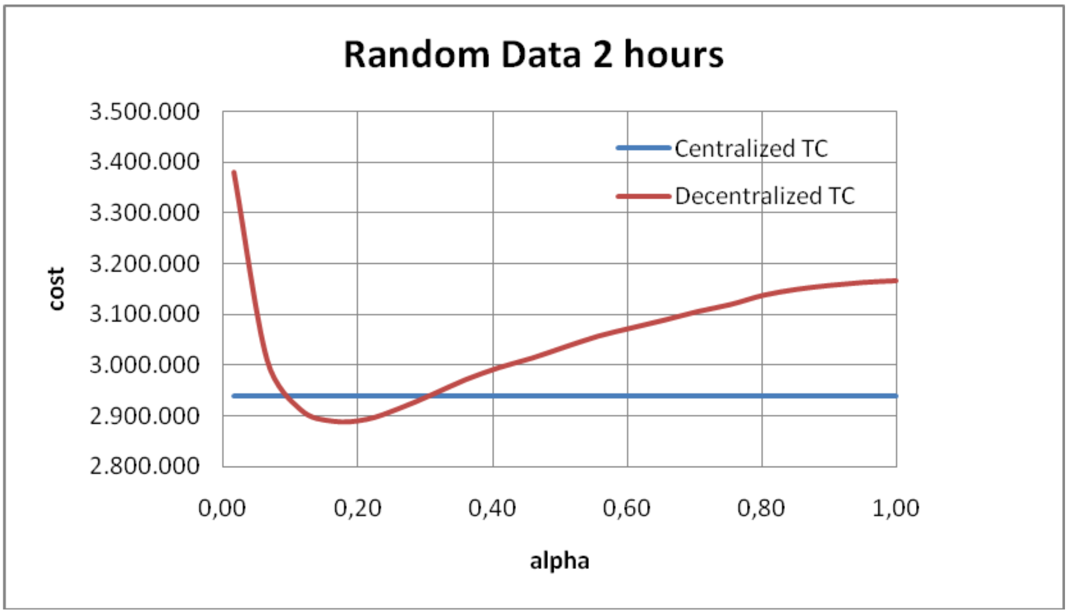

Figure C.1 : Random data with 2 hours waiting time target 65/7 CW replenishment lead time/transportation time

Appendix C.2 Model-2 company data 1 hour graphics

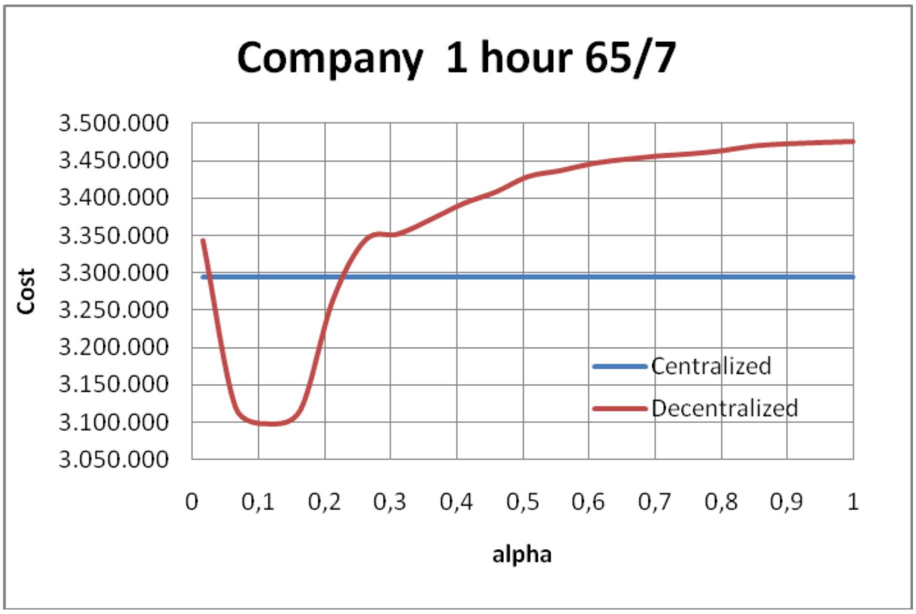

Figure C.2 : 1 hours waiting time target 65/7 CW replenishment lead time/transportation time

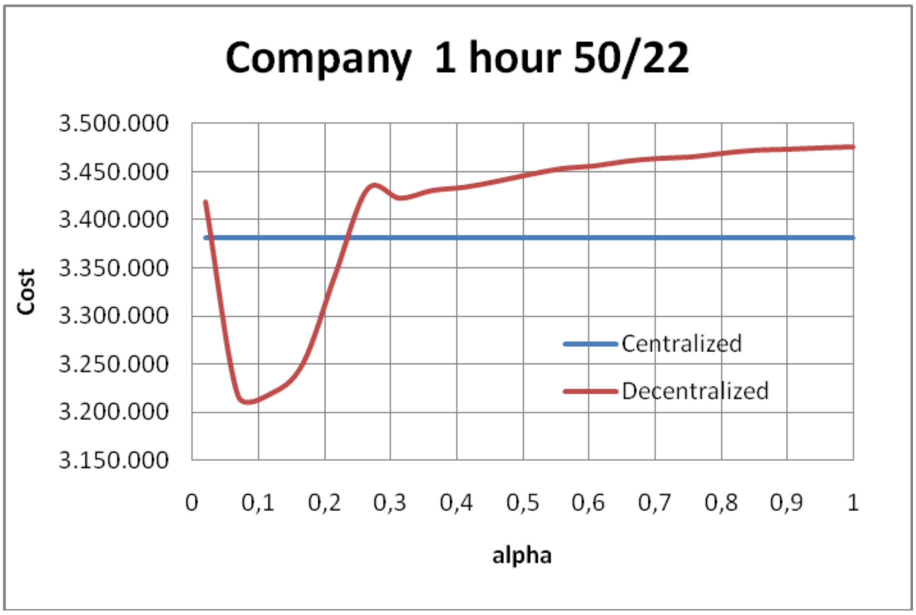

Figure C.3 : 1 hours waiting time target 50/22 CW replenishment lead time/transportation time

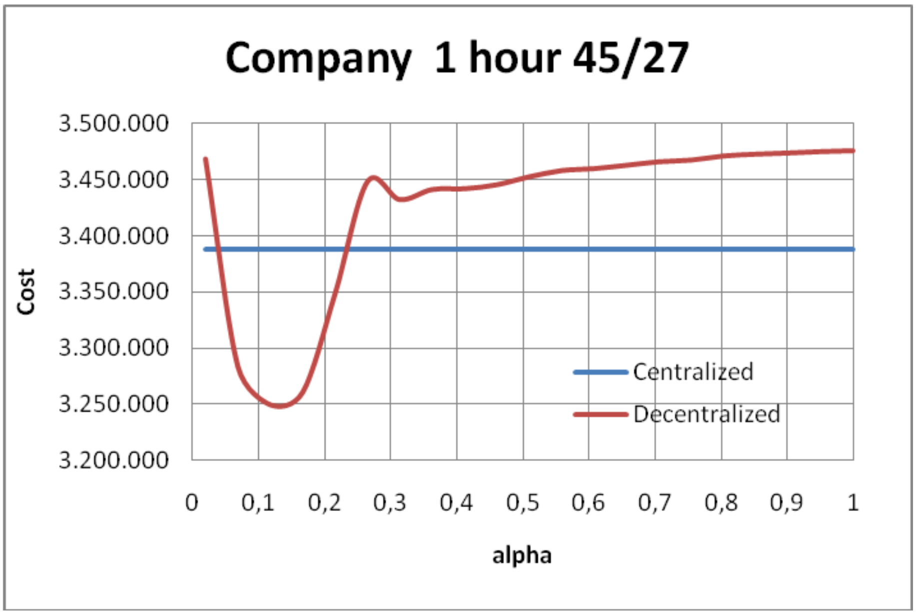

Figure C.4 : 1 hours waiting time target 45/27 CW replenishment lead time/transportation time

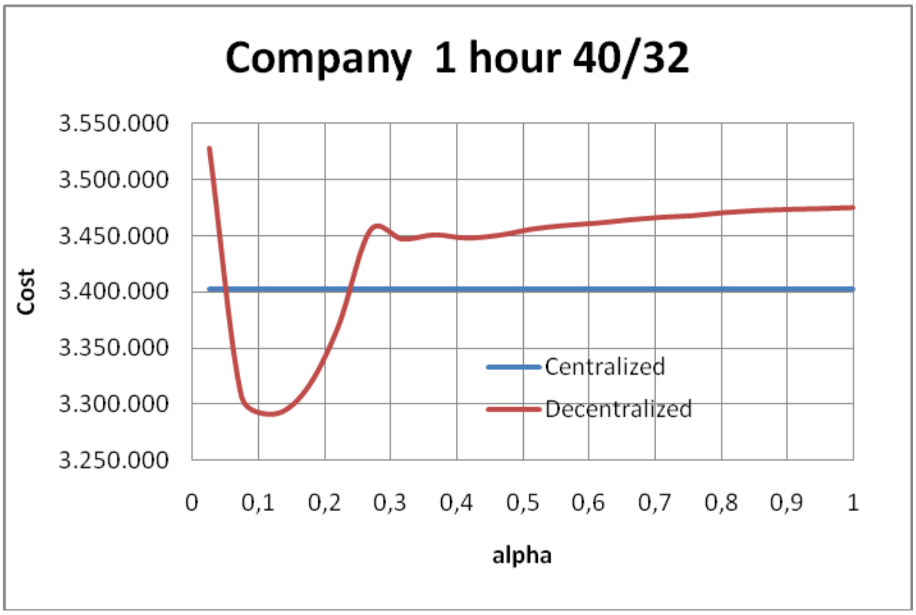

Figure C.5 : 1 hours waiting time target 40/32 CW replenishment lead time/transportation time

Appendix C.3 Model-2 company data 2 hour graphics

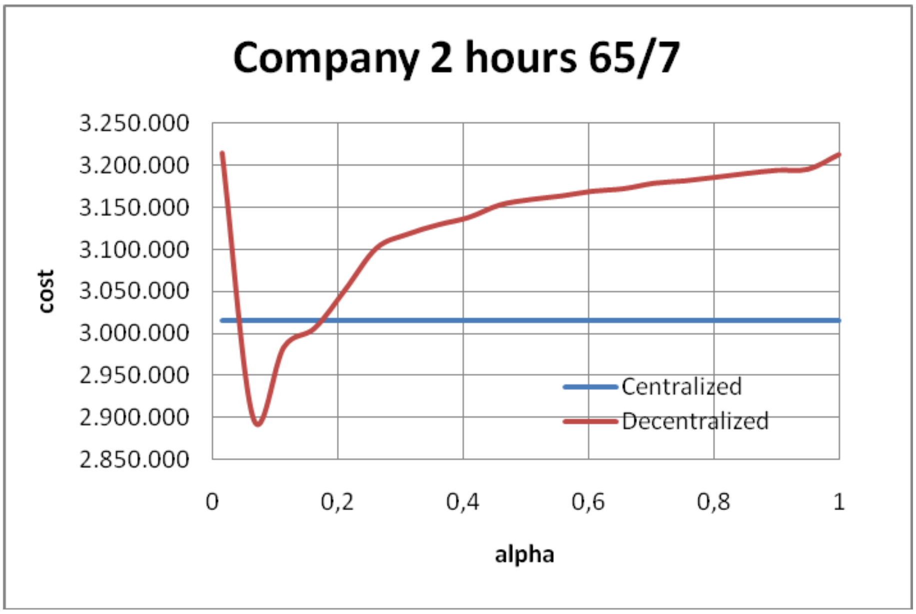

Figure C.6 : 2 hours waiting time target 65/7 CW replenishment lead time/transportation time

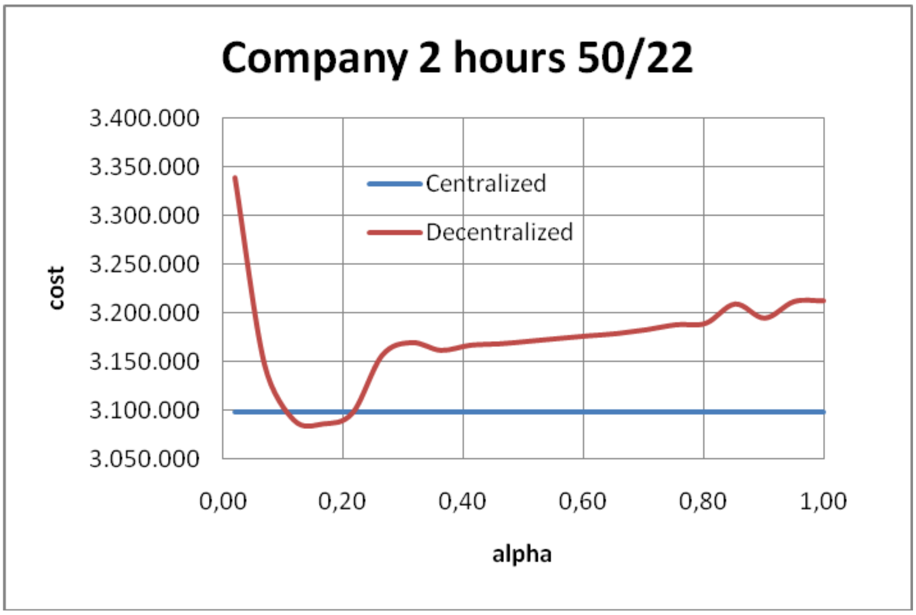

Figure C.7 : 2 hours waiting time target 50/22 CW replenishment lead time/transportation time

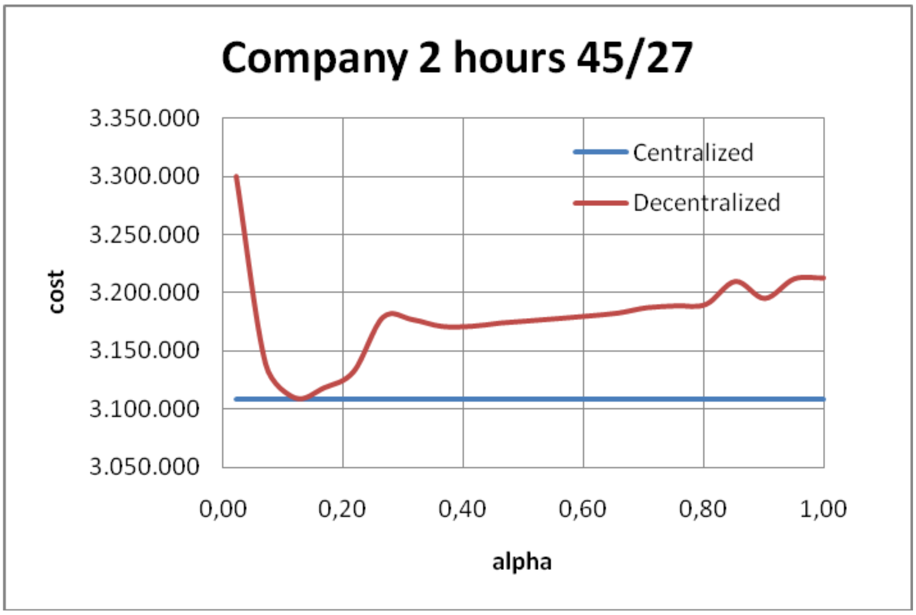

Figure C.8 : 2 hours waiting time target 45/27 CW replenishment lead time/transportation time

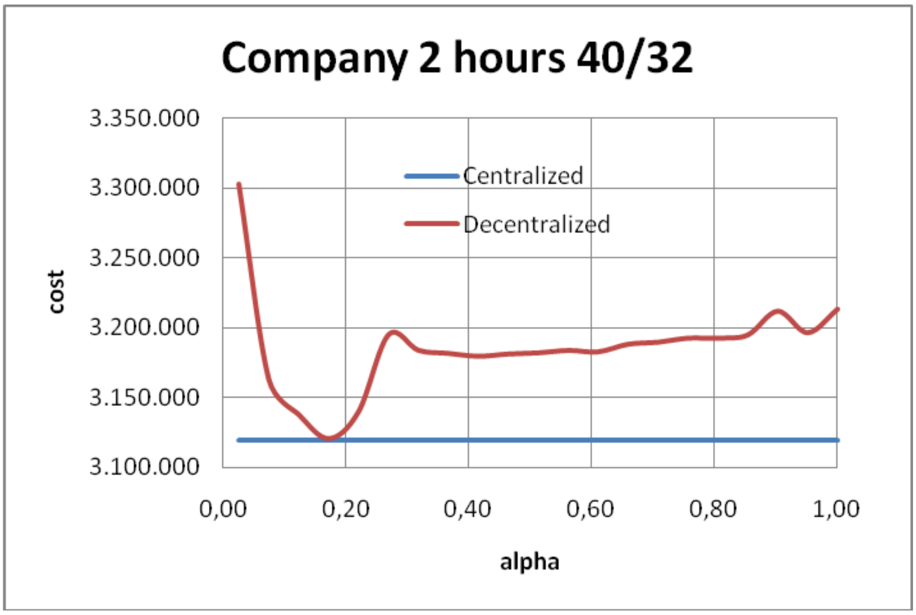

Figure C.9 : 2 hours waiting time target 40/32 CW replenishment lead time/transportation time

Appendix C.4 Model-2 company data 4 hour graphics

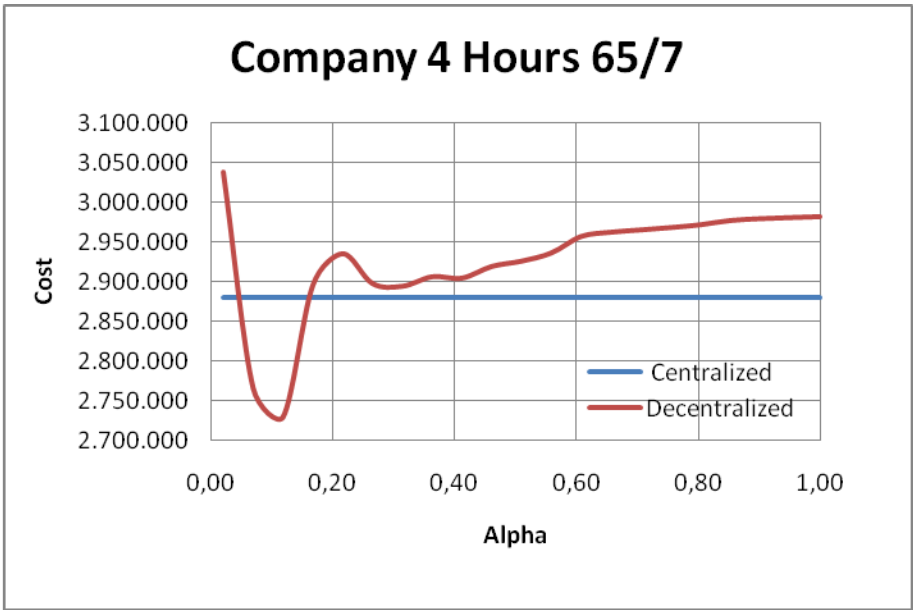

Figure C.10 : 4 hours waiting time target 65/7 CW replenishment lead time/transportation time

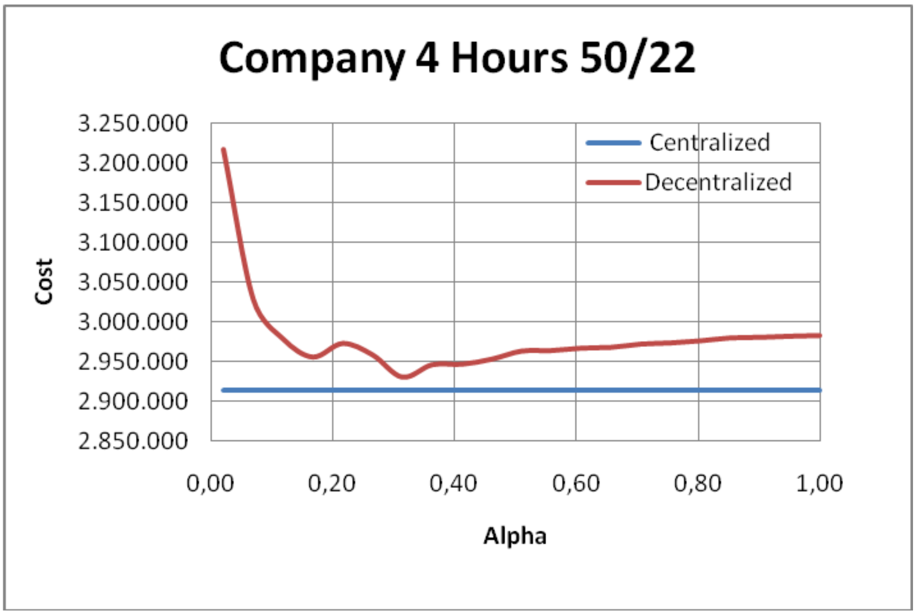

Figure C.11 : 4 hours waiting time target 50/22 CW replenishment lead time/transportation time

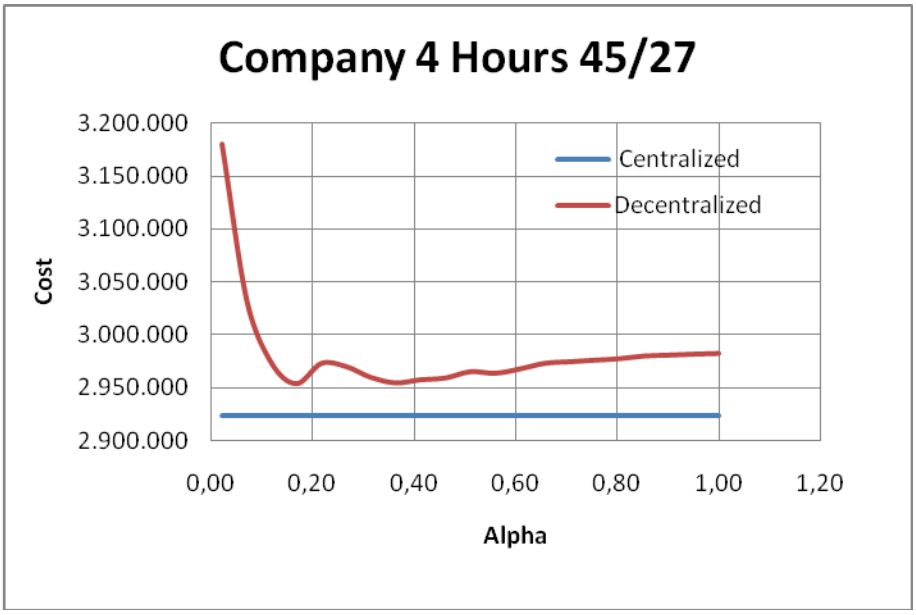

Figure C.12 : 2 hours waiting time target 45/27 CW replenishment lead time/transportation time

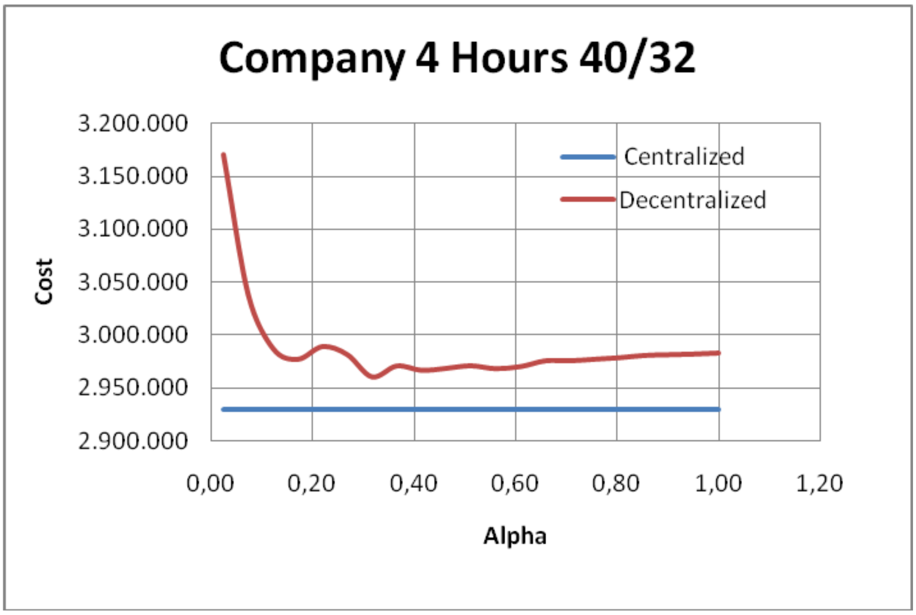

Figure C.13 : 2 hours waiting time target 45/27 CW replenishment lead time/transportation time

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